Modeling and Performance Analysis of Simplified Two-Diode Model of Photovoltaic Cells

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For a quick and consistent photovoltaic (PV) module design, an effective, fast, and exact simulator is crucial to examine the performance of the photovoltaic cell under partial or quick variation of temperature and irradiance. The most prevalent modeling strategy is to apply an equivalent (electrical) circuit that encompasses together non-linear and linear mechanisms. This work proposes the modeling and analysis for a four-parameter two-diode photovoltaic cell model based on the manufacturer's data-sheet. The proposed model needs only four parameters compared to the previously developed seven-parameter two-diode model to reduce the computational complexity. To develop a specific model of photovoltaic cells, the fundamental requirement is the data of temperature and irradiance. The variation of these variables totally affects the output constraints like current, voltage, and power. Thus, it is substantial to design a precise model of the photovoltaic cell module with a reduced computation period. The two-diode photovoltaic module with four constraints is identified to be more accurate and have improved performance compared to a one-diode model particularly at lower irradiance. To confirm the accuracy of the proposed model the method is applied on two different photovoltaic modules. The proposed model and modeling method are helpful for power electronic designers who require a fast, accurate, simple, and easy to implement method for use in photovoltaic system simulation. The electrical equivalent circuit and standard equations of photovoltaic cells are analyzed and the proposed two-diode model is simulated using MATLAB/Simulink software and validated for poly-crystalline and mono-crystalline solar cells under standard test conditions.

Keywords: one-diode photovoltaic model, two-diode photovoltaic model, poly-crystalline solar cell, circuit constraints, mono-crystalline solar cell

INTRODUCTION

In recent years, several models have been developed including the single-diode $R_s$ model, $R_P$ model, and double-diode and triple-diode model [1–3]. The most modest scheme is a one-diode PV model (ideal case) as it involves only three variables: current at short circuit, voltage at open circuit, and diode ideality factor. The enhanced type of the model includes the insertion of series resistance $R_s$ to the equivalent circuit [4]. While this model suffers from inconsistencies with the change in the temperature values as it does not consider the voltage temperature coefficient. The upgraded version is the $R_P$ model by the insertion of a shunt resistor to the equivalent circuit [5]. Though this model has improved accuracy, with the insertion of $R_P$ the computational parameters are increased to five which leads to more computation time.
In general, most of the constructors only provide data about constraints like voltage at open circuit ($V_{oc}$), current at short circuit ($I_{sc}$), peak or maximum power ($P_{mpp}$), current at $P_{mpp}$ ($I_{mpp}$), and voltage at $P_{mpp}$ ($V_{mpp}$) at standard operating conditions and inappropriately these data are far away from what is essential for modeling because a PV cell is used to functioning at various ecological conditions. The non-linear performance of current-voltage characteristics requires the alteration of constraints by using the manufacturer data sheet [6, 7].

So far, many researchers have developed a single-diode model by making an assumption that nonappearance of recombination loss occurs in the depletion layer. In reality, it is not possible to satisfactorily model by using a single diode. Consideration of this loss results in a more exact model, identified as the two-diode model [8]. But, with the insertion of the extra diode it increases the constraints to seven and the new constraints include reverse saturation current $I_{DS2}$ and ideality factor $C_2$ of the second diode. The main task is now to evaluate the values of the model constraints while keeping a realistic computational energy. The key knowledge of this paper, to develop a detailed model of a two-diode PV cell module, is by simplifying the current equation and thereby reducing the constraints to four. The precision of this PV model is confirmed by two different solar PV cells from the constructor information sheet and behavior performance is compared with a one-diode $R_{sh}$ model. This enhanced model can be useful for researchers who work on the precise modeling of photovoltaic (PV) modules.

**FUNDAMENTALS AND CIRCUIT MODEL OF PHOTOVOLTAIC CELLS**

**Effective Principle of Photovoltaic Cells**

A basic structure of a typical photovoltaic cell is represented in Figure 1. A photovoltaic cell essentially consists of two films doped in a different way and behaves as a semiconductor diode through its p-n junction, which is exposed to incident light [9]. When the photovoltaic cell is exposed to this light, electron-hole pairs are generated which initiates the flow of the electric current if the circuit is closed from cathode (N type) to anode (P type).

By this convention, the electric current direction is always chosen with reference to the direction of movement of positive charges. Consequently, the direction of current in the load circuit is shown from a positive to negative terminal.

**Electrical Equivalent Circuit of One-Diode Photovoltaic Cell Model**

The one-diode model with a series and parallel resistor is represented in Figure 2 [3]. For practical reasons, we cannot
neglect the $R_{SE}$ and $R_{SH}$ resistor in photovoltaic cell modeling. With the addition of these resistors, the constraints are now increased to five which also lengthens the computation time. This model is the most popular due its ease, accuracy, and easy of implementation. Despite of its advantages, the model’s accuracy will worsen at lower irradiance [10].

**MODELING OF A PHOTOVOLTAIC CELL AND DETERMINATION OF CONSTRAINTS**

**Modeling of a Two-Diode Photovoltaic Cell**

The two-diode PV model is represented in [Figure 3][2]. Obviously, two more new constraints now need to be considered: the reverse saturation diode current $I_{DS2}$ and ideality factor $C_2$. The current $I_{DS2}$ compensates for the consequence of recombination loss in the depletion area [11].

By applying KVL to [Figure 3], we get the expression for current $I$:

$$I = I_L - I_{D1} - I_{D2} - I_{SH}$$

$$(1) = I_L - I_{D1} - I_{D2} - \frac{V_0 + IR_{SE}}{R_{SH}}$$

$I_L$ is the light or photo current, $I_{D1}$ and $I_{D2}$ is the current through diode 1 and diode 2, $I_{SH}$ is the current through the shunt resistor \(\frac{V_0 + IR_{SE}}{R_{SH}}\), $R_{SE}$ and $R_{SH}$ are series and shunt resistances, $V_0$ is applied voltage across diode, and $I$ is module output current [12].

Currents through diodes 1 and 2 are given by:

$$I_{D1} = \frac{V_0 + IR_{SE}}{e^{\frac{V_0}{kT_{Ac}}} - 1}$$

$$I_{D2} = \frac{V_0 + IR_{SE}}{e^{\frac{V_0}{kT_{Ac}}} - 1}$$

$$I = I_L - I_{D1}\left[\left(e^{\frac{V_0}{kT_{Ac}}} - 1\right)\right] - \frac{V_0 + IR_{SE}}{R_{SH}}$$

$$(2) = I_L - I_{D1}\left[\left(e^{\frac{V_0}{kT_{Ac}}} - 1\right)\right] - \frac{V_0 + IR_{SE}}{R_{SH}}$$

$I_{D1}$ and $I_{D2}$ are reverse saturation diode current, $C_1$ and $C_2$ are the diode ideality factor of 1 and 2, $N_{SE}$ is series-connected PV cells, $V_T$ is thermal voltage \(\frac{kT_{Ac}}{q}\), $V_T$ is approximately 25.856 mV at 300 Kelvin, $q$ is (1.602 X 10^{-19}), $C$ is electron charge, $K$ = (1.38 X 10^{-23}) is a Boltzmann constant, and $T_{Ac}$ is the cell’s absolute temperature in Kelvin.

Light or photo current [9] is given by

$$I_L = (I_{SC} + \gamma SC\Delta T_{Ac}) \frac{G_{ir}}{G_{SC}}$$

$$G_{ir} - \text{irradiance in } \frac{W}{m^2}, G_{SC} - \text{irradiance at the standard test condition (STC) = 1,000 } \frac{W}{m^2}, T_{Ac} = \Delta T_{Ac,ref} (\text{Kelvin}),$$

where $\gamma$ — voltage temperature coefficient (V/K).

In making the model simple for analysis, the seven constraints are reduced to four by assuming the $I_{DS} = I_{DS1} = I_{DS2}$ and \((\frac{(C_1 + C_2)}{P}) = 1\) as described in [12]. Therefore.

$$I_{DS} = I_{DS1} = I_{DS2} = \frac{I_{SC} + \gamma SC\Delta T_{Ac}}{e^{\frac{V_0 + \gamma SC\Delta T_{Ac}}{kT_{Ac}}} - 1}$$

$$I_{DS} = I_{DS1} = I_{DS2} = \frac{I_{SC} + \gamma SC\Delta T_{Ac}}{e^{\frac{V_0 + \gamma SC\Delta T_{Ac}}{kT_{Ac}}} - 1}$$

**Determination of Photovoltaic Module Constraints**

Owing to its complication in analysis and constraints estimation, the analysis and simulation of the PV cell in the two-diode model is not so simple. To make it easier to study the following assumptions are considered: the $I_{DS} = I_{DS1} = I_{DS2}$ and \((\frac{(C_1 + C_2)}{P}) = 1\). By inputting the temperature and irradiance in Equations (3) and (5), the light current and diode saturation currents are estimated by using the constructor datasheet. By setting the values of ideality factors $C_1 = 1$ and $C_2 = 1.2$ yields the best suitable outcomes in the current-voltage curve of the PV cell model. These alterations make the two-diode model into its simplified form and therefore attractive for PV system simulation. In general, the constructor gives data of current at short circuit ($I_{SC}$), voltage at open circuit ($V_0$) and peak or maximum power ($P_{mpp}$). Now we will evaluate the current equation shown below for three conditions: current ($I_{SC}$) at short circuit, voltage ($V_0$) at open circuit, and peak or maximum power ($P_{mpp}$) point condition.

$$I = I_L - I_{D1} - I_{D2} - \frac{V_0 + IR_{SE}}{R_{SH}}$$

At the short circuit condition

$$I = I_{SC,STC}; V_0 = 0$$

$$I_{SC,STC} = I_{L,STC} - I_{D1,STC} - I_{D2,STC} - \frac{I_{SC,STC}R_{SE}}{R_{SH}}$$

where, $I_{D1,STC} = I_{D1,STC}\left[\left(e^{\frac{I_{SC,STC}R_{SE}}{kT_{Ac}}} - 1\right)\right]$ and $I_{D2,STC} = I_{D2,STC}\left[\left(e^{\frac{I_{SC,STC}R_{SE}}{kT_{Ac}}} - 1\right)\right]$.
FIGURE 4 | Complete sub-system model of proposed two-diode photovoltaic (PV) model.

FIGURE 5 | Saturation current ($I_{DS}$) of proposed two-diode model.

FIGURE 6 | Light current ($I_L$) of proposed two-diode model.
Table 1 | Component specifications from constructor data sheet.

| Constraints | Mono-crystalline DS-A1-80 solar panel | Poly-crystalline Solarex MSX-64 |
|-------------|--------------------------------------|----------------------------------|
| Maximum power (P_{mpp}) | 80 W | 64 W |
| Voltage at P_{mpp} (V_{mpp}) | 17.2 V | 17.5 V |
| Current at P_{mpp} (I_{mpp}) | 4.66 A | 3.66 A |
| Voltage at open circuit (V_{oc}) | 21.3 V | 21.3 V |
| Current at short circuit (I_{sc}) | 5.29 A | 4 A |
| Series-connected cell (N_{SE}) | 36 | 36 |
| Voltage temperature coefficient (γ_{vo}) | -0.38 V/°C | -80 mV/°C |
| Voltage temperature coefficient (γ_{sc}) | 0.13 °C | 0.65 °C |

At the open circuit condition

\[ I = 0; V_0 = \frac{V_{o,STC}}{R_{SH}} \]  \hspace{1cm} (7)

From Equation (7)

\[ I_{L,STC} = I_{D1,STC} + I_{D2,STC} + \frac{V_{o,STC}}{R_{SH}} \]  \hspace{1cm} (8)

where \[ I_{D1,STC} = I_{D1,STC} \left( e^{\frac{V_{o,STC}}{V_{T,STC}}} - 1 \right) \] and \[ I_{D2,STC} = I_{D2,STC} \left( e^{\frac{V_{o,STC}}{V_{T,STC}}} - 1 \right) \]

At the maximum power condition

\[ I_{mpp,STC} = I_{L,STC} - I_{D1,STC} - I_{D2,STC} - \frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{R_{SH}} \]  \hspace{1cm} (9)

Table 2 | Estimated values of proposed two-diode model.

| Constraints | Mono-crystalline DS-A1-80 solar panel | Poly-crystalline Solarex MSX-64 |
|-------------|--------------------------------------|----------------------------------|
| Maximum power (P_{mpp}) | 80.08 W | 64.159 W |
| Voltage at P_{mpp} (V_{mpp}) | 17.04 V | 17.46 V |
| Current at P_{mpp} (I_{mpp}) | 4.69 A | 3.67 A |
| Voltage at open circuit (V_{oc}) | 21.3 V | 21.3 V |
| Current at short circuit (I_{sc}) | 5.29 A | 4 A |
| Light current (I_{L}) | 5.29 A | 4.01 A |
| Saturation currents (I_{D1} = I_{D2}) | 5.207 x 10^{-10} A | 3.937 x 10^{-10} A |
| Series resistance (R_{SE}) | 0.34 Ω | 0.3 Ω |
| Shunt resistance (R_{SH}) | 157.22 Ω | 160.4 Ω |

Table 3 | Estimated values of one-diode R_{SH} model.

| Constraints | Mono-crystalline DS-A1-80 solar panel | Poly-crystalline Solarex MSX-64 |
|-------------|--------------------------------------|----------------------------------|
| Maximum power (P_{mpp}) | 80.07 W | 63.55 W |
| Voltage at P_{mpp} (V_{mpp}) | 16.61 V | 17.46 V |
| Current at P_{mpp} (I_{mpp}) | 4.67 A | 3.64 A |
| Voltage at open circuit (V_{oc}) | 21.3 V | 21.3 V |
| Current at short circuit (I_{sc}) | 5.29 A | 4 A |
| Light current (I_{L}) | 5.28 A | 4.01 A |
| Saturation currents (I_{D1} = I_{D2}) | 2.423 x 10^{-8} A | 1.62 x 10^{-8} A |
| Diode ideality factor (C) | 1.2 | 1.2 |
| Series resistance (R_{SE}) | 0.22 Ω | 0.2 Ω |
| Shunt resistance (R_{SH}) | 282.33 Ω | 310 Ω |
TABLE 4 | Comparison of estimated values at maximum power ($P_{mpp}$) of the two-diode model and one-diode ($R_{SH}$) model for a mono-crystalline (DS-A1-80) solar cell.

| Constraints | Manufacturer data at STC | Two-diode model | One-diode ($R_{SH}$) model | % relative error of two-diode model | % relative error of one-diode model |
|-------------|--------------------------|-----------------|----------------------------|------------------------------------|----------------------------------|
| Maximum power ($P_{mpp}$) | 80 W | 80.08 W | 80.07 W | 0.099 | 0.087 |
| Voltage at $P_{mpp}$ ($V_{mpp}$) | 17.2 V | 17.04 V | 16.61 V | 0.938 | 3.552 |
| Current at $P_{mpp}$ ($I_{mpp}$) | 4.66 A | 4.68 A | 4.67 A | 0.639 | 0.214 |
| Voltage at open circuit ($V_o$) | 21.3 V | 21.3 V | 21.3 V | 0.00 | 0.00 |
| Current at short circuit ($I_{SC}$) | 5.29 A | 5.29 A | 5.29 A | 0.00 | 0.00 |

TABLE 5 | Comparison of estimated values at maximum power ($P_{mpp}$) of the two-diode model and one-diode ($R_{SH}$) model for a poly-crystalline solar cell (MSX-64).

| Constraints | Manufacturer data at STC | Two-diode model | One-diode ($R_{SH}$) model | % relative error of two-diode model | % relative error of one-diode model |
|-------------|--------------------------|-----------------|----------------------------|------------------------------------|----------------------------------|
| Maximum power ($P_{mpp}$) | 64 W | 64.159 W | 63.55 W | 0.247 | 0.708 |
| Voltage at $P_{mpp}$ ($V_{mpp}$) | 17.5 V | 17.47 V | 17.47 V | 0.171 | 0.171 |
| Current at $P_{mpp}$ ($I_{mpp}$) | 3.66 A | 3.67 A | 3.64 A | 0.272 | 0.549 |
| Voltage at open circuit ($V_o$) | 21.3 V | 21.3 V | 21.3 V | 0.00 | 0.00 |
| Current at short circuit ($I_{SC}$) | 4 A | 4 A | 4 A | 0.00 | 0.00 |

From Equation (12)

\[
\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{R_{SH}} = \frac{I_{L,STC} - I_{D1,STC} - I_{D2,STC} - I_{mpp,STC}}{V_{mpp,STC} + I_{mpp,STC}R_{SE}}
\]

where $P_{mpp}$ is the peak or maximum power, $V_{mpp,STC}$ is the voltage at $P_{mpp}$, and $I_{mpp,STC}$ is the current at $P_{mpp}$. Diode saturation currents at the maximum power condition is given by the relation as shown below:

\[
I_{D1,STC} = I_{D1,STC}[(e^{\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{V_{mpp,STC} + I_{mpp,STC}R_{SE}}} - 1)]
\]

\[
I_{D2,STC} = I_{D2,STC}[(e^{\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{V_{mpp,STC} + I_{mpp,STC}R_{SE}}} - 1)]
\]

**Determination of $R_{SE}$ and $R_{SH}$ Constraints**

Several analytical and numerical approaches [3, 6, 7, 9, 13–15] have been proposed in the literature to evaluate the constraints of one-diode and two-diode models. In this analysis the constraints $R_{SE}$ and $R_{SH}$ are estimated by the same method as described previously [9]. By using effective iteration process the value of $R_{SE}$ and $R_{SH}$ can be estimated with the help of Equation (10). The main takeaway is that the value of $R_{SE}$ and $R_{SH}$ are selected such that calculated power $P_{mpp}$ must be equal to experimental power provided by the constructor data sheet $P_{mpp,STC}$. This iteration procedure initiates from $R_{SE} = 0$ which must vary in directive until it matches the calculated maximum power of $P_{mpp,STC}$, and simultaneously $R_{SH}$ is calculated.
SIMULATION RESULTS AND DISCUSSION

The modeling technique characterized in this work is confirmed by measured constraints of certain photovoltaic (PV) cell modules. Two different PV modules; mono-crystalline DS-A1-80\(^1\) and poly-crystalline MSX-64\(^2\) are employed for verification. We can observe that the calculated values slightly deviate from the manufacturer data sheet value at STC. However, the poly-crystalline (MSX-64) cell exactly fits the manufacturer data for the proposed two-diode model. Figures 8, 9 characterize the power vs. voltage curve of \(R_{SH}\) and the proposed two-diode model for mono-crystalline and poly-crystalline solar cells at STC. Comparative analysis of the current vs. voltage curve of \(R_{SH}\) and the proposed two-diode model for the DS-A1-80 solar cell at various temperatures and irradiance levels are represented in Figures 10, 11. Comparative analysis of the current vs. voltage curve of \(R_{SH}\) and proposed two-diode model for the MSX-64 solar cell at various temperatures and irradiance levels are represented in Figures 12, 13. From the results we can observe that both models exhibited the same performance at STC. However, the proposed two-diode model showed better performance compared to the \(R_{SH}\) model precisely at lesser irradiance levels especially for open circuit voltage. The comparison of estimated values at maximum power (\(P_{mpp}\)) of the two-diode model and one-diode (\(R_{SH}\)) model for mono-crystalline (DS-A1-80) and poly-crystalline (MSX-64) solar cells are shown in Tables 4, 5.

CONCLUSION

For a quick and consistent photovoltaic module design, an effective, fast, and exact simulator is crucial to examine the performance of the photovoltaic cell under a partial or quick variation of temperature and irradiance. The most prevalent modeling strategy is to apply an equivalent (electrical) circuit that encompasses both non-linear and linear mechanisms. In the proposed work, an improved typical two-diode system aimed at photovoltaic cell modules was developed. Distinct from past photovoltaic modules recommended by many researchers, the developed work only needed the calculation of four constraints. A modest and fast iterative technique was used to estimate \(R_{SE}\) and \(R_{SH}\) resistances. The accuracy of the developed model was examined by using experimental data provided by the constructors of two different photovoltaic cell modules. Its performable behavior was compared with one-diode \(R_{SH}\) models. It was observed that the proposed two-diode model had improved performance specifically at open circuit voltage and short circuit current and maximum power point conditions irrespective of variations in temperature and irradiance. Specifically, it showed better performance and accuracy at lesser irradiance situations. The proposed model was validated for mono-crystalline and poly-crystalline solar cells under standard test conditions.

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\(^1\)Available online at: http://www.possharp.com/ds-a1-80-solar-panel-from-anjidasol-solarenergysciencetechnology_p462201154d.aspx (accessed January 31, 2021).

\(^2\)Available online at: https://www.solarelectricsupply.com/media/custom/upload/Solarex-MSX64.pdf (accessed January 31, 2021).
FIGURE 12 | Comparative analysis of current (A) vs. voltage (V) curve for one-diode $R_{SH}$ and proposed two-diode model for MSX-64 with different irradiance points at STC (25°C).

FIGURE 13 | Comparative analysis of current (A) vs. voltage (V) curve for one-diode $R_{SH}$ and proposed two-diode model for MSX-64 with different temperature points at STC (1,000 KW/m²).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.
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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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