



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.

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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.

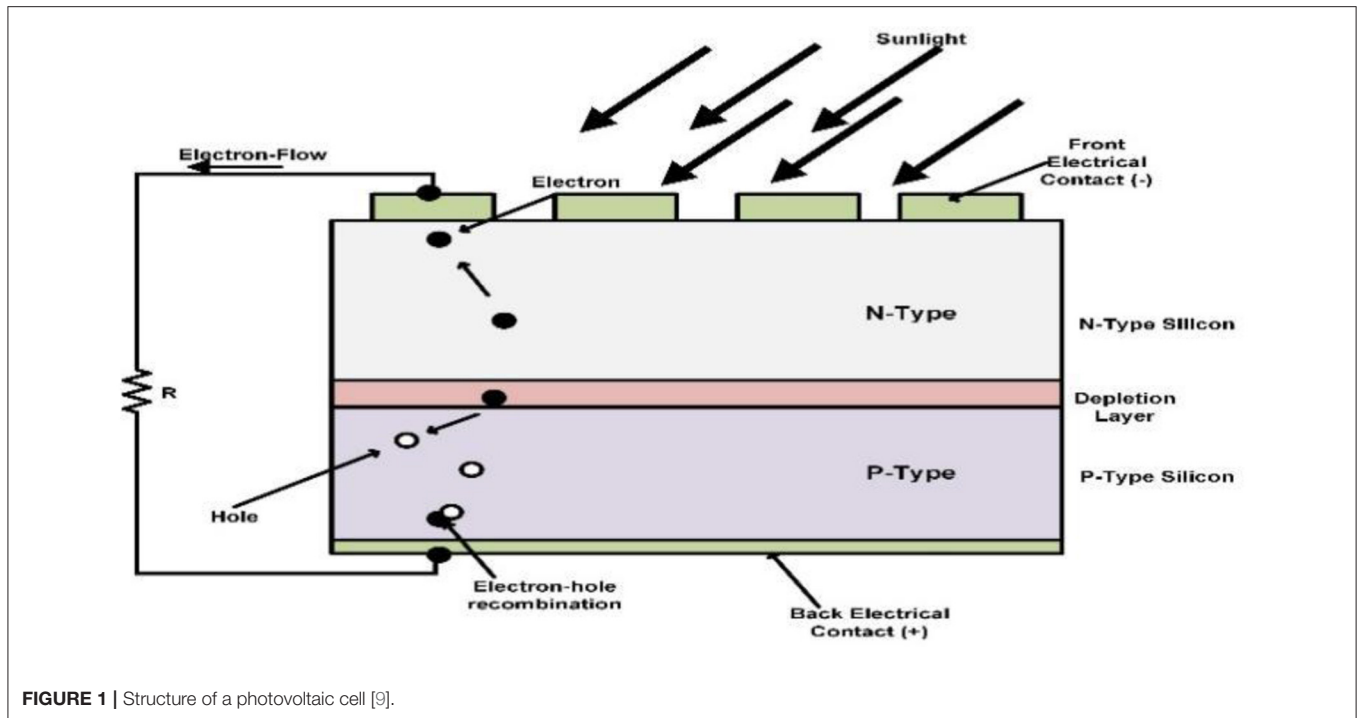


FIGURE 1 | Structure of a photovoltaic cell [9].

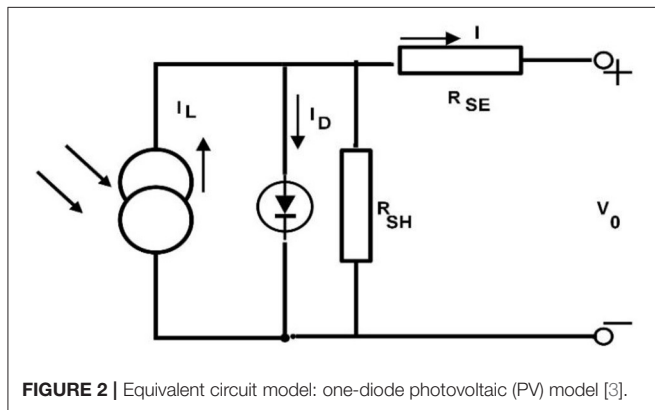


FIGURE 2 | Equivalent circuit model: one-diode photovoltaic (PV) model [3].

In general, most of the constructors only provide data about constraints like voltage at open circuit (V_o), 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

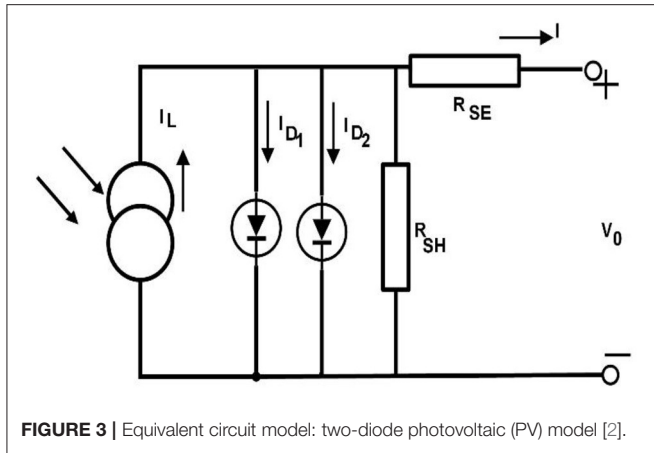


FIGURE 3 | Equivalent circuit model: two-diode photovoltaic (PV) model [2].

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 :

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

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

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

$$I_{D1} = I_{DS1} \left[\left(e^{\frac{V_0 + IR_{SE}}{C_1 V_T N_{SE}}} \right) - 1 \right]$$

$$I_{D2} = I_{DS2} \left[\left(e^{\frac{V_0 + IR_{SE}}{C_2 V_T N_{SE}}} \right) - 1 \right]$$

$$I = I_L - I_{D1} - I_{D2} - \frac{V_0 + IR_{SE}}{R_{SH}} \quad (2)$$

I_{DS1} and I_{DS2} 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 $= \frac{K T_{Ac}}{q}$, V_T is approximately

25.856 mV at 300 Kelvin, q is (1.602×10^{-19}) , C is electron charge, $K = (1.38 \times 10^{-23}) \frac{\text{Joule}}{\text{Kelvin}}$ is a Boltzmann constant, and T_{Ac} is the cell's absolute temperature in Kelvin.

Light or photo current [9] is given by

$$I_L = (I_{SC} + \gamma_{SC} \Delta T_{Ac}) \frac{G_{ir}}{G_{SC}} \quad (3)$$

G_{ir} - irradiance in $\frac{W}{m^2}$, G_{SC} - irradiance at the standard test condition (STC) $= 1,000 \frac{W}{m^2}$, $T_{Ac} = T_{Ac} - \Delta T_{Ac,ref}$ (Kelvin), $T_{Ac,ref} = (25 + 273 = 298 \text{ Kelvin})$, I_{SC} is the cell's short circuit current at STC (25°), and γ_{SC} is the current temperature coefficient (A/K).

$$I_{DS} = I_{DS1} = I_{DS2} = \frac{I_{SC} + \gamma_{SC} \Delta T_{Ac}}{\left(e^{\frac{V_0 + \gamma_V \Delta T_{Ac}}{V_{\Delta T} \left(\frac{C_1 + C_2}{p} \right)} - 1} \right)} \quad (4)$$

where γ_V - 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 $\left(\frac{C_1 + C_2}{p} \right) = 1$ as described in [12]. Therefore,

$$I_{DS} = I_{DS1} = I_{DS2} = \frac{I_{SC} + \gamma_{SC} \Delta T_{Ac}}{\left(e^{\frac{V_0 + \gamma_V \Delta T_{Ac}}{V_{\Delta T}} - 1} \right)} \quad (5)$$

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 $\left(\frac{C_1 + C_2}{p} \right) = 1$. 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 module. 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

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

$$I_{SC,STC} = I_{L,STC} - I_{D1,STC} - I_{D2,STC} - \frac{I_{SC,STC} R_{SE}}{R_{SH}} \quad (6)$$

where, $I_{D1,STC} = I_{DS1,STC} \left[\left(e^{\frac{I_{SC,STC} R_{SE}}{C_1 V_T N_{SE}}} \right) - 1 \right]$ and $I_{D2,STC} = I_{DS2,STC} \left[\left(e^{\frac{I_{SC,STC} R_{SE}}{C_2 V_T N_{SE}}} \right) - 1 \right]$

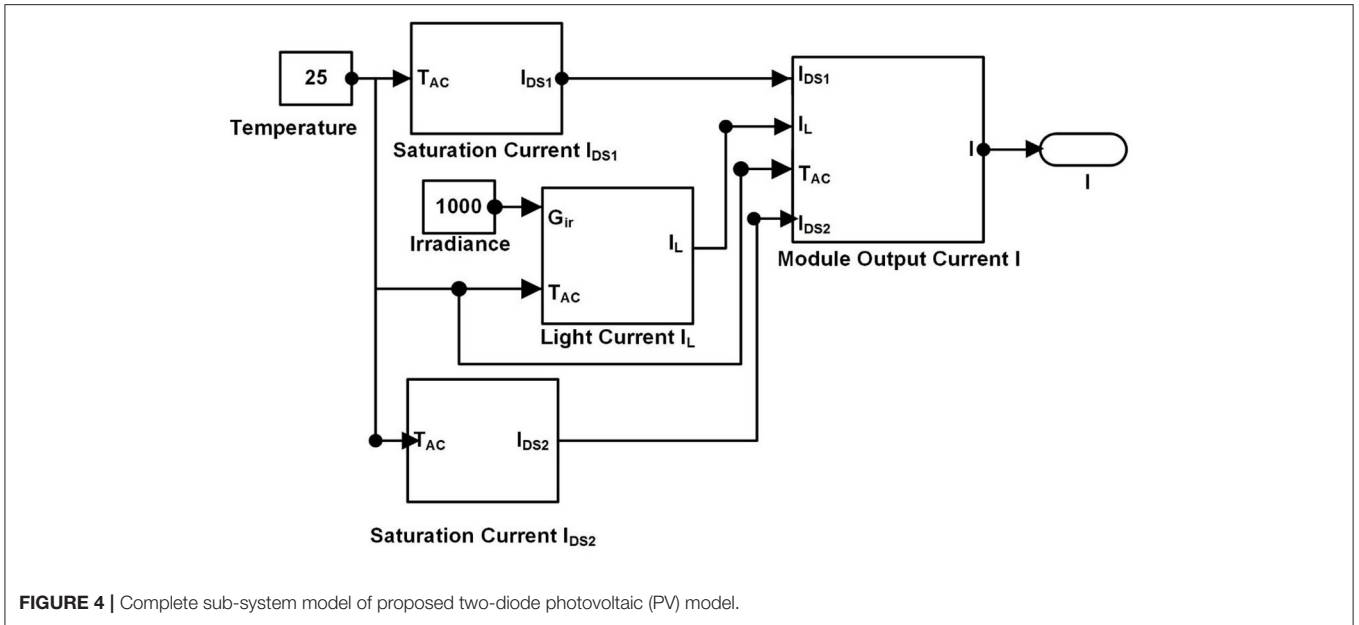


FIGURE 4 | Complete sub-system model of proposed two-diode photovoltaic (PV) model.

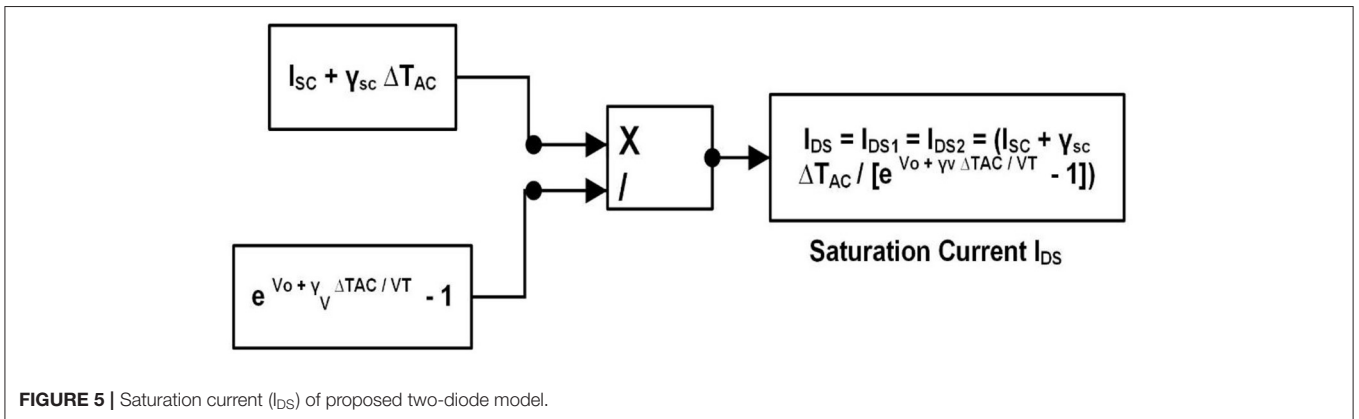


FIGURE 5 | Saturation current (I_{DS}) of proposed two-diode model.

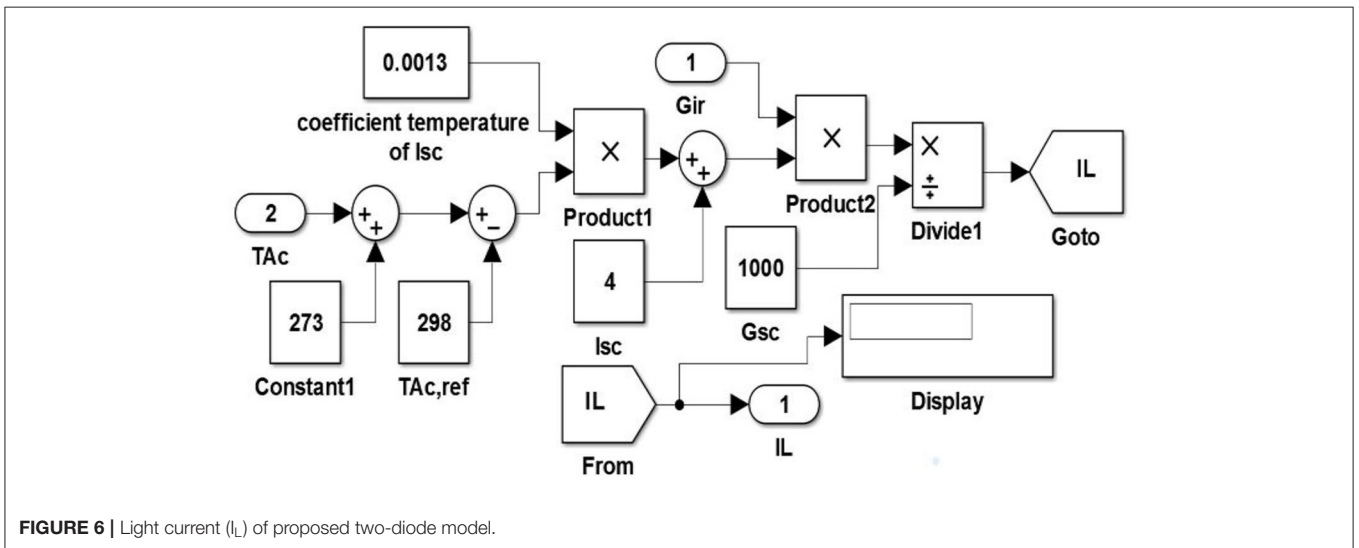


FIGURE 6 | Light current (I_L) of proposed two-diode model.

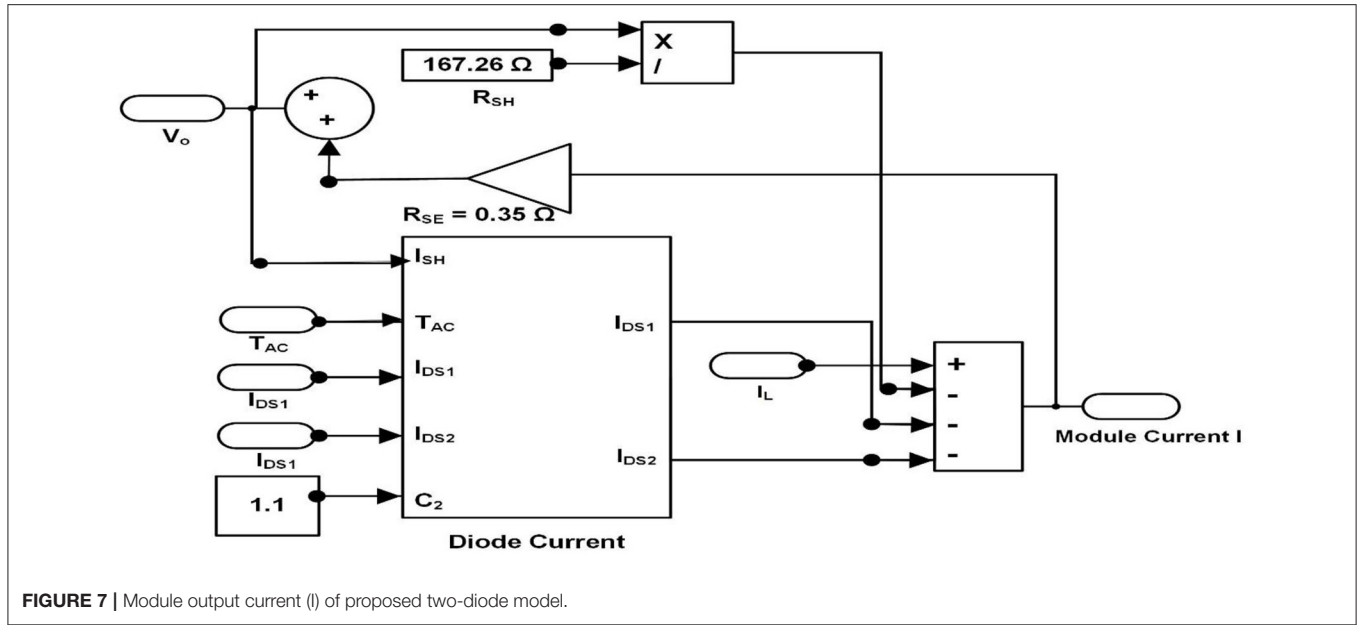


FIGURE 7 | Module output current (I) of proposed two-diode model.

TABLE 1 | Component specifications from constructor data sheet.

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

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

Constraints	Mono-crystalline DS-A1-80 solar panel	Poly-crystalline Solarex MSX-64 panel
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_o)	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 ($I_{DS1} = I_{DS2}$)	5.207×10^{-10} A	3.937×10^{-10} A
Series resistance (R_{SE})	0.34 Ω	0.3 Ω
Shunt resistance (R_{SH})	157.22 Ω	160.4 Ω

At the open circuit condition

$$I = 0; V_0 = V_{o,STC}$$

$$0 = I_{L,STC} - I_{D1,STC} - I_{D2,STC} - \frac{V_{o,STC}}{R_{SH}} \quad (7)$$

From Equation (7)

$$I_{L,STC} = I_{D1,STC} + I_{D2,STC} + \frac{V_{o,STC}}{R_{SH}} \quad (8)$$

where $I_{D1,STC} = I_{DS1,STC}[(e^{\frac{V_{o,STC}}{C_1 V_T N_{SE}}} - 1)]$ and $I_{D2,STC} = I_{DS2,STC}[(e^{\frac{V_{o,STC}}{C_2 V_T N_{SE}}} - 1)]$

At the maximum power condition

$$I_{mpp,STC} = I_{L,STC} - I_{D1,STC} - I_{D2,STC} - \frac{V_{mpp,STC} + I_{mpp,STC} R_{SE}}{R_{SH}} \quad (9)$$

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

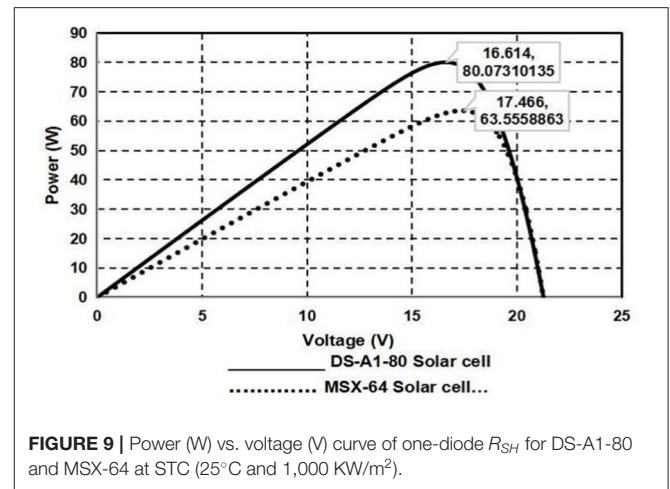
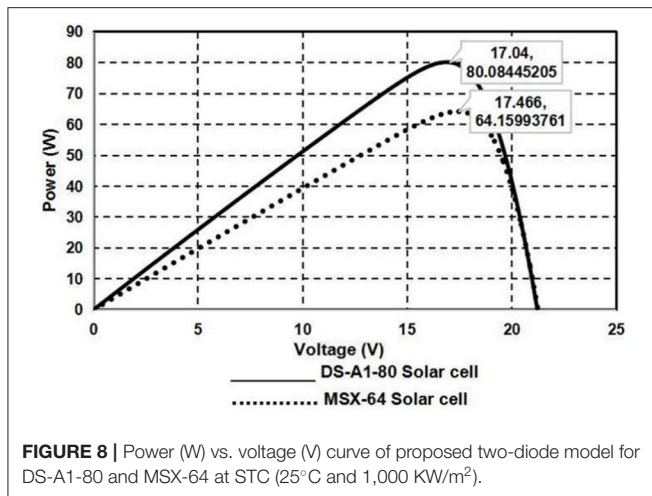
Constraints	Mono-crystalline DS-A1-80 solar panel	Poly-crystalline Solarex MSX-64 panel
Maximum power (P_{mpp})	80.07 W	63.55 W
Voltage at P_{mpp} (V_{mpp})	16.61 V	17.46 V
Current at P_{mpp} (I_{mpp})	4.67 A	3.64 A
Voltage at open circuit (V_o)	21.3 V	21.3 V
Current at short circuit (I_{SC})	5.29 A	4 A
Light current (I_L)	5.28 A	4.01 A
Saturation currents ($I_{DS1} = I_{DS2}$)	2.423×10^{-8} A	1.82×10^{-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	4.69 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)

$$R_{SH} = \frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{I_{L,STC} - I_{D1,STC} - I_{D2,STC} - I_{mpp,STC}} \quad (10)$$

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:

$$I_{D1,STC} = I_{D1,STC} \left[\left(e^{\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{C_1 V_T N_{SE}}} \right) - 1 \right]$$

$$I_{D2,STC} = I_{D2,STC} \left[\left(e^{\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{C_2 V_T N_{SE}}} \right) - 1 \right]$$

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.

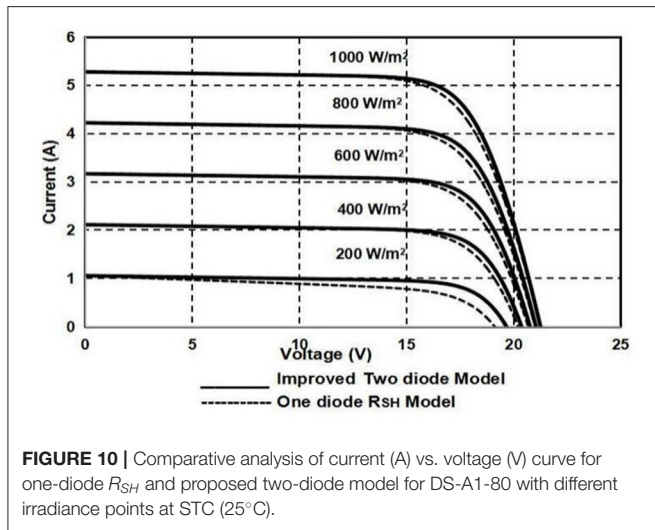


FIGURE 10 | Comparative analysis of current (A) vs. voltage (V) curve for one-diode R_{SH} and proposed two-diode model for DS-A1-80 with different irradiance points at STC (25°C).

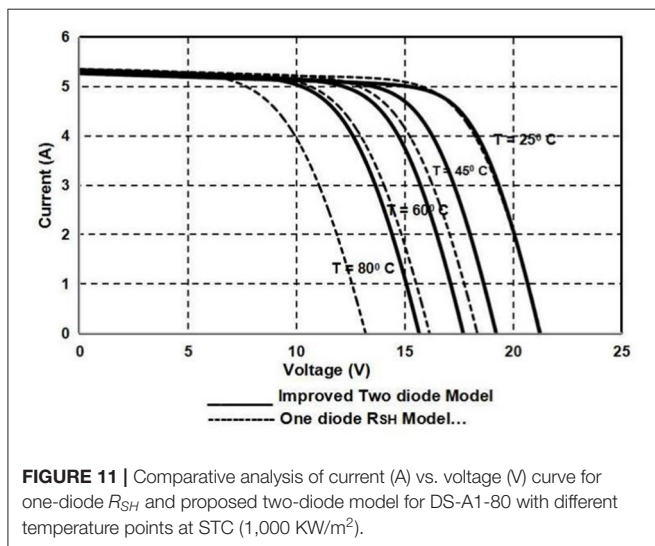


FIGURE 11 | Comparative analysis of current (A) vs. voltage (V) curve for one-diode R_{SH} and proposed two-diode model for DS-A1-80 with different temperature points at STC (1,000 KW/m²).

SIMULATION OF PROPOSED TWO-DIODE MODEL

The complete sub-system group model of the proposed two-diode photovoltaic (PV) module is represented in **Figure 4**. By using Equations (2)–(5), detailed simulation models were developed in MATLAB/Simulink. The simulation block diagram of diode saturation current is represented in **Figure 5**, light current is represented in **Figure 6**, and module output current is represented in **Figure 7**. The component specifications of both mono-crystalline and poly-crystalline PV modules are shown in **Table 1**. **Table 2** illustrates the determined values of the proposed two-diode model and **Table 3** shows the constraints for the one-diode R_{SH} model. **Tables 4, 5** summarize the study of relative error of P_{mpp} , V_{mpp} , I_{mpp} , V_o , and I_{SC} of both mono and poly-crystalline solar cells. The proposed two-diode model actually requires only four constraints because saturation current $I_{DS1} = I_{DS2} = I_{DS}$ whereas $C_1 = 1$, C_2 is chosen > 1.2 and the value of p is recommended to be a value larger than 2.2 [12].

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-A1-80¹ and poly-crystalline MSX-64² 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.

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

²Available online at: <https://www.solarelectricsupply.com/media/custom/upload/Solarex-MSX64.pdf> (accessed January 31, 2021).

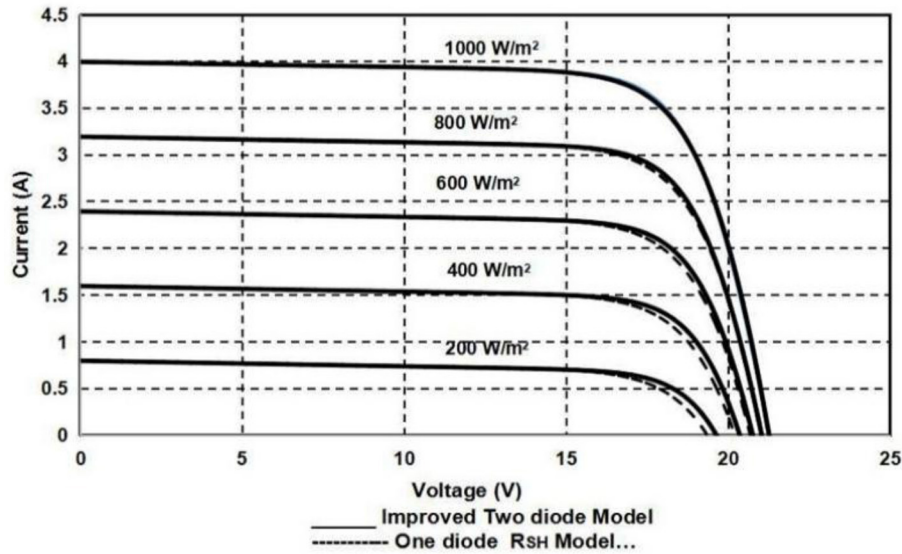


FIGURE 12 | Comparative analysis of current (A) vs. voltage (V) curve for one-diode R_{SH} and proposed two-diode model for MSX-64 with different irradiance points at STC (25°C).

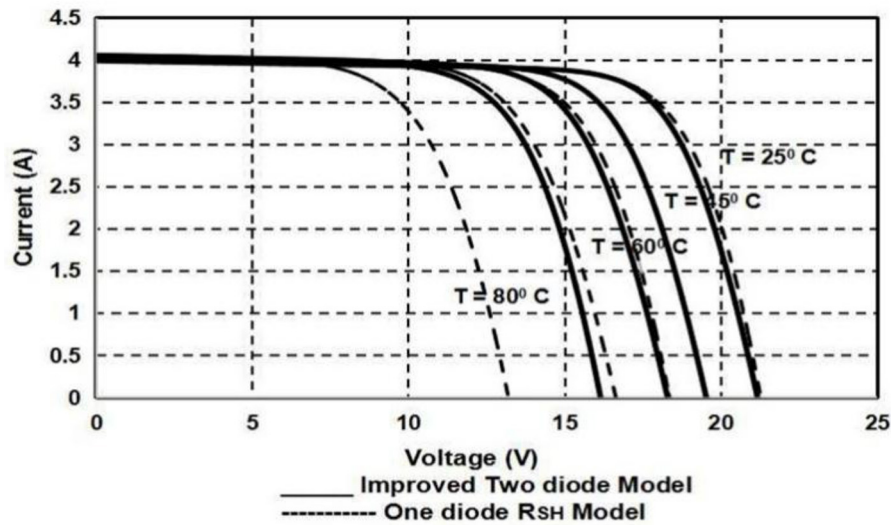


FIGURE 13 | Comparative analysis of current (A) vs. voltage (V) curve for one-diode R_{SH} and proposed two-diode model for MSX-64 with different temperature points at STC (1,000 kW/m²).

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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