Modeling and Performance Analysis of Simplified Three-Diode Photovoltaic Module

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Abstract- Developing the mathematical model of photovoltaic (PV) cell, to simulate the module and predict their actual performance at varying temperature and irradiance condition, is very significant for evaluation of photovoltaic cell, as well as for dynamic analysis of dc-dc converters and design of maximum power point algorithms. This work proposes the analysis and modeling of photovoltaic module using the three-diode five parameter model formed based on manufacturer's datasheet. The constraints of electrical equivalent circuit of photovoltaic cell are analyzed by solving the non-linear current-voltage equation based on manufacturer datasheet provided at standard operating conditions with reduced computation period by using an effective iteration procedure. The photovoltaic current-voltage formulation is analyzed at three main points specifically at open circuit, short circuit and maximum power point condition. This model is identified to have better performance and precise compared to two-diode model mainly at lesser irradiance and higher temperature levels. To verify the accuracy and conformity of the proposed model the method is applied on two different multi or poly-crystalline photovoltaic module and obtained results were compared by manufacturer performance data. By using the standard mathematical equations of photovoltaic cell this model is developed and simulated in MATLAB/Simulink software.

Keywords: Three-diode Photovoltaic model, Two-diode Photovoltaic model, Multi-crystalline solar cell, Iteration procedure, Shunt resistance

1. Introduction

Modelling of photovoltaic (PV) cell needs to predict the performable behavior of actual photovoltaic cell at various ecological conditions and to produce its power-voltage and current-voltage curves. The most common modelling method is to employ equivalent (electrical) circuit that includes both non-linear and linear mechanisms. In general, the manufacturer's datasheet only tabulate about some constraints like open circuit voltage (V_o), short circuit current (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 unfortunately these data is far away from what is critical for modelling because photovoltaic cell is used to operate at various irradiance and temperature points. The non-linear behavior of current-voltage characteristics needs the adjustment of parameters by using manufacturer data. Several researchers have been proposed some model based on single-diode R_S model, R_P model, double-diode and three-diode photovoltaic model [3], [4] and [7]. The modest system is one-diode photovoltaic model it comprises only three parameters in ideal case like current at short circuit, voltage at open circuit and ideality factor of diode. The improved form of the ideal model is addition of series resistance R_s to the electrical equivalent circuit [10]. Although this model suffers from irregularities with the variation in the temperature values as it not considered the voltage temperature coefficient. The advanced form of model is the R_P model by addition of parallel resistor to the equivalent circuit [11]. This R_P model has improved performance in comparison to one diode R_S model.

In past many researchers have presented single diode model by making an assumption that absence of recombination loss in depletion layer. In actual it is not possible to reasonably develop a model by means of single diode. In practice for precise model by consideration of this recombination loss results in more actual model identified as a two-diode model [16]. The improved version of both one diode and two-diode model is by insertion of third diode in parallel with the two diodes which taken into consideration of recombination of the defect regions results in more accurate model identified as a three-diode model [2]. Though these enhanced models possess improved accuracy but with the insertion of additional diodes which results in more computational parameters and leads to more computational complexity. The main objective is now to evaluate the model constraints while keeping a realistic computational energy.

The significant knowledge of this paper is to develop a comprehensive model of three-diode photovoltaic module is by simplifying the current equation and thereby reducing the constraints to five. Multi or polycrystalline silicon material is progressively useful for the production of photovoltaic cell owing to its low cost. In order to realize the performance of multi-crystalline solar cell, it is significant to study their electrical properties [12]. The output performance of this simplified three-diode model is confirmed by two different multi or polycrystalline solar cells from manufacturer performance data and precision of this model is compared with two diode model. This simplified model can be useful for researchers those who works on the accurate modelling of photovoltaic module for design of maximum power point tracking algorithms and power converters for energy storage devices.

2. Electrical Equivalent Circuit and Modeling of Photovoltaic Cell

2.1 Equivalent Circuit model of One-diode and Two-diode Photovoltaic Cell

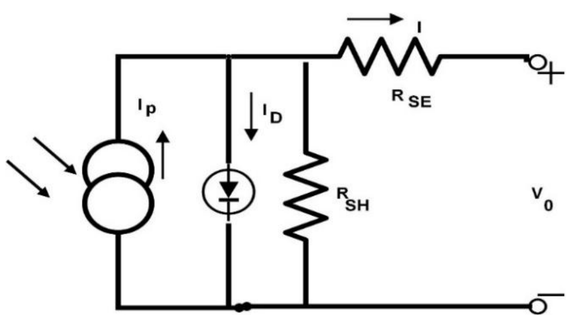

Figure 1: One-Diode R_{SH} Photovoltaic Cell equivalent circuit model [7]

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The one-diode R_{SH} model considers one diode connected in parallel to the constant current source with series resistance R_{SE} and shunt resistance R_{SH} is shown in Figure 1 [7]. In case of modeling of one-diode model the number of constraints will become five. The constraints are photo or incident current I_P, diode saturation current I_{DS}, ideality factor of diode C, series resistance R_{SE} and shunt resistance R_{SH}. The one-diode R_{SH} model is identified as most popular and easy to implement. In spite of its advantages the model precision will become worse at lesser irradiance [8].

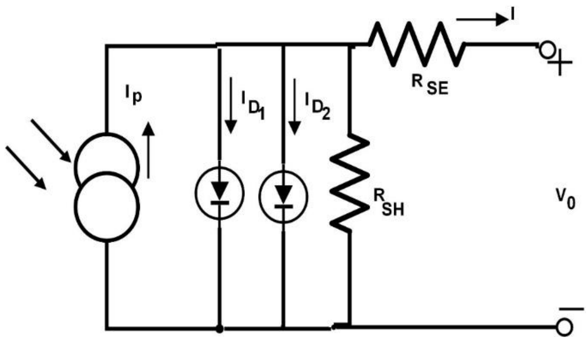

Figure 2: Two-diode Photovoltaic Cell equivalent circuit model [4]

The Two-diode model considers two diodes connected in parallel to the constant current source as shown in Figure 2 [4] obviously now two more new constraints are essential to be considered is the reverse saturation diode current I_{DS2} and ideality factor C_2. The current I_{DS2} compensates the consequence of recombination loss in the depletion area [15]. The number of constraints will become seven in case of two-diode model. The constraints are photo or incident current I_P, diode saturation current I_{DS1} and I_{DS2}, ideality factor of diode C_1 and C_2, series resistance R_{SE} and shunt resistance R_{SH}. Two-diode model is identified as more accurate model and better performance especially at lower irradiance.

2.2 Modeling of Three-diode photovoltaic (PV) cell

The Three-diode model considers three diodes connected in parallel to the constant current source as shown in Figure 3 [2] obviously now two more new constraints are essential to be considered while modeling is the reverse saturation diode current I_{DS3} and ideality factor C_3. The current I_{DS3} compensates the consequence of recombination in the defects area [2]. The number of constraints will become nine in case of three-diode model. The constraints are photo or incident current I_P, diode saturation current I_{DS1}, I_{DS2} and I_{DS3}, ideality factor of diode C_1, $C_2$and C_3, series resistance R_{SE} and shunt resistance R_{SH}. Three-diode model is identified to be more accurate model and better performance especially at lower irradiance and higher temperature points.

By applying KVL to Fig.3 we get the expression for output or module current I:

$$I = I_p - I_{D1} - I_{D2} - I_{D3} - \frac{V_0 + IR_{SE}}{R_{SH}} \qquad (1)$$

I_P is the Photo or incident current, I_{D1}, I_{D2} and I_{D3} is the diode currents, I_{SH} is Current through 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 output current of module [1].

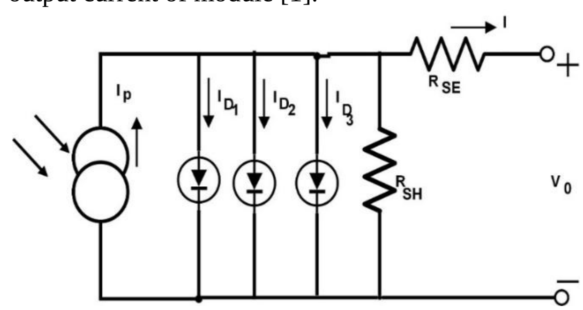

Figure 3: Three-Diode photovoltaic Cell equivalent circuit model

Currents through diodes 1 and 2 is given by

$$I_{D1} = I_{Ds1}[(e^{\frac{V_O + IR_{SE}}{C_1 V_T N_{SE}}}) - 1]$$

$$I_{D2} = I_{Ds2}[(e^{\frac{V_O + IR_{SE}}{C_2 V_T N_{SE}}}) - 1] \text{ and } I_{D3} = I_{Ds3}[(e^{\frac{V_O + IR_{SE}}{C_3 V_T N_{SE}}}) - 1]$$

$$I = I_p - I_{Ds1}[(e^{\frac{V_O + IR_{SE}}{C_1 V_T N_{SE}}}) - 1] - I_{Ds2}[(e^{\frac{V_O + IR_{SE}}{C_2 V_T N_{SE}}}) - 1] - I_{Ds3}[(e^{\frac{V_O + IR_{SE}}{C_3 V_T N_{SE}}}) - 1] - \frac{V_0 + IR_{SE}}{R_{SH}} \quad (2)$$

I_{Ds1}, I_{Ds2} and I_{Ds3} are reverse saturation diode current, C_1, C_2 and C_3 is Diode Ideality factor of 1,2 and greater than 2, N_{SE} is number of series connected PV cell's, V_T is called as Thermal Voltage = $\frac{K\,T_{Ac}}{q}$, V_T is approximately 25.856 mV at 300 Kelvin, q is ($1.602\,X\,10^{-19}$) C is electron charge, K – ($1.38\,X\,10^{-23}$) $^{Joule}/_{Kelvin}$ is a Boltzmann constant, T_{Ac} is Cell's absolute temperature in Kelvin. Photo current [9] is given by

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

G_{ir} – Irradiance in $^{W}/_{m^2}$, G_{SC} – Irradiance at Standard Test Condition (STC) = 1000 $^{W}/_{m^2}$, $\Delta T_{Ac} = T_{Ac} - T_{Ac,ref}$ (Kelvin), $T_{Ac,ref}$ - (25 + 273 = $298\,Kelvin$), I_{SC} is Cell's short circuit current of Cell at STC (25^0), K_{SC} is temperature coefficient of current (A/K).

Simplified diode saturation current equation in terms of temperature coefficient (K_V) can be written as

$$I_{DS} = I_{DS1} = I_{DS2} = I_{DS3} = \frac{I_{SC} + K_{SC}\Delta T_{Ac}}{(e^{\frac{V_0 + K_V \Delta T_{Ac}}{V_T[\frac{C_1 + C_2 + C_3}{P}]}} - 1)} \quad (4)$$

where

K_V – temperature coefficient of voltage (V/K)

In development of three-diode model it required to estimate nine constraints which makes analysis very complicated and not so simple for simulation of PV module. For ease analysis and to make the model simple the nine constraints are reduced to five as described in [1] the same assumption can be applied for modeling of three-diode model. To make it simple in analysis the following assumptions are considered: the $I_{DS} = I_{DS1} = I_{DS2} = I_{DS3}$ and $^{(C_1 + C_2 + C_3)}/_{p}$) = 1. In the equations (3) and (5) by substituting the temperature and irradiance inputs the photo current and diode saturation currents are estimated based on data provided by constructor. By setting the values of ideality factors C_1 = 1, C_2 = 2.2, C_3 is chosen greater than 2 yields in the best suitable outcomes in current-voltage curve of PV cell module [2]. These changes make three-diode model to easy system and attractive for PV system simulator and only five constraints to be evaluated.

Therefore

$$I_{DS} = I_{DS1} = I_{DS2} = I_{DS3} = \frac{I_{SC} + K_{SC}\Delta T_{Ac}}{(e^{\frac{V_0 + K_V \Delta T_{Ac}}{V_T}} - 1)} \quad (5)$$

2.2 Determination of R_{SE} and R_{SH} Constraints

Several analytical and numerical approaches [3], [5], [6], [9], [13] and [14] have been proposed in the literature to evaluate the constraints of one-diode and two-diode model. In this work the constraints R_{SE} *and* R_{SH} is evaluated by same approach as described in [9]. The key information is the value of R_{SE} *and* R_{SH} are selected such that calculated power $P_{mpp,C}$ must be equal to experimental power $P_{mpp,STC}$ provided by constructor data sheet. Figure 4 illustrates the flow chart of iteration process to adjust the current-voltage curve. This iteration process initiates from $R_{SE} = 0$ which must vary in path until to match the calculated maximum power to $P_{mpp,STC}$ must be equal to experimental power $P_{mpp,STC}$ and simultaneously R_{SH} is then calculated. By adjusting the values of R_{SE} *and* R_{SH} based on the fact that at only one pair (R_{SE} , R_{SH}) which guarantees that $P_{mpp,C}$ = $P_{mpp,STC}$ = $V_{mpp}.I_{mpp}$ at maximum power point of current-voltage curve.

In general manufacturer gives data of current at short circuit (I_{SC}), voltage at open circuit (V_o) and peak or maximum power (P_{mpp}). Now evaluate the current equation shown below at three conditions: current (I_{SC}) at short circuit, voltage (V_o) at open circuit and peak or maximum power (P_{mpp}) point condition.

$$I = I_p - I_{D1} - I_{D2} - I_{D3} - \frac{V_0 + IR_{SE}}{R_{SH}}$$

At short circuit condition

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

$$I_{SC,STC} = I_{p,STC} - I_{D1,STC} - I_{D2,STC} - I_{D3,STC} - \frac{I_{SC,STC}R_{SE}}{R_{SH}} \quad (6)$$

Where, $I_{D1,STC} = I_{Ds1,STC}[(e^{\frac{I_{SC,STC}R_{SE}}{C_1 V_T N_{SE}}}) - 1]$ $I_{D2,STC} = I_{Ds2,STC}[(e^{\frac{I_{SC,STC}R_{SE}}{C_2 V_T N_{SE}}}) - 1]$ and $I_{D3,STC} = I_{Ds3,STC}[(e^{\frac{I_{SC,STC}R_{SE}}{C_3 V_T N_{SE}}}) - 1]$

At open circuit condition

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

$$0 = I_{p,STC} - I_{D1,STC} - I_{D2,STC} - I_{D3,STC} - \frac{V_{o,STC}}{R_{SH}} \quad (7)$$

From equation (7)

$$I_{p,STC} = I_{D1,STC} + I_{D2,STC} + I_{D3,STC} + \frac{V_{o,STC}}{R_{SH}} \quad (8)$$

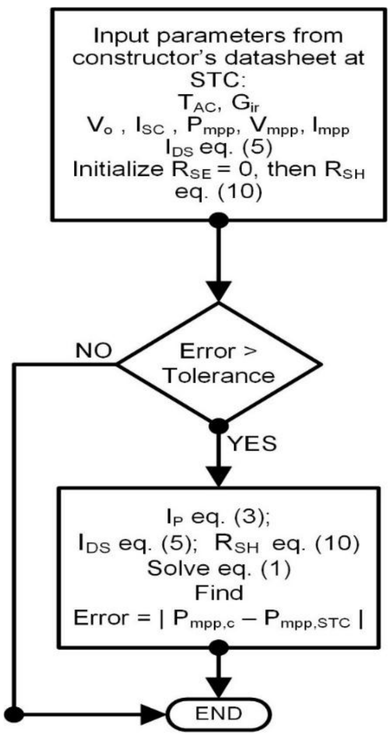

Figure 4: Flow Chart for Iteration process

Where $I_{D1,STC} = I_{Ds1,STC}[(e^{\frac{V_{o,STC}}{C_1 V_T N_{SE}}}) - 1]$, $I_{D2,STC} = I_{Ds2,STC}[(e^{\frac{V_{o,STC}}{C_2 V_T N_{SE}}}) - 1]$ and

$$I_{D3,STC} = I_{Ds3,STC}[(e^{\frac{V_{o,STC}}{C_3 V_T N_{SE}}}) - 1]$$

At maximum power condition

$$I_{mpp,STC} = I_{p,STC} - I_{D1,STC} - I_{D2,STC} - I_{D3,STC} - \frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{R_{SH}} \quad (9)$$

From equation (9)

$$\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{R_{SH}} = I_{p,STC} - I_{D1,STC} - I_{D2,STC} - I_{D3,STC} - I_{mpp,STC}$$

$$R_{SH} = \frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{I_{p,STC} - I_{D1,STC} - I_{D2,STC} - I_{D3,STC} - I_{mpp,STC}} \quad 10)$$

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

$I_{D1,STC} = I_{Ds1,STC}[(e^{\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{C_1 V_T N_{SE}}}) - 1]$, $I_{D2,STC} = I_{Ds2,STC}[(e^{\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{C_2 V_T N_{SE}}}) - 1]$ and $I_{D3,STC} = I_{Ds3,STC}[(e^{\frac{V_{mpp,STC} + I_{mpp,STC}R_{SE}}{C_3 V_T N_{SE}}}) - 1]$

By using iteration process the value of R_{SE} *and* R_{SH} can be estimated with help of equation (10).

4. Simulation of Proposed Three-diode Model

Based on the equations (2), (3), (4) and (5) it is simple to frame an overall simulation model by MATLAB/Simulink software. The overall three-diode model and sub-system group model are represented in Figure 5 and Figure 6. The detailed simulation models of diode saturation currents are represented in Fig.7 of proposed three diode model. Simulation model of Photo current and module output currents of proposed three diode model are simulated and represented in Figure 8 and Figure 9

5. Results and Discussion

The modelling system proposed in this work is confirmed by estimated constraints of certain PV cell modules. The proposed model is validated by two different multi or polycrystalline PV modules; KC200GT [17] and MSX-64 [18]. The product specifications of two different PV modules are shown in Table 1. Table 2 illustrates the measured values of proposed three-diode model and Table 3 illustrates the measured values of two-diode model. Table 4 and Table 5 summarizes the study of relative error of P_{mpp}, V_{mpp}, I_{mpp}, V_o and I_{SC} of both poly-crystalline solar cell. From Table 4 and Table 5 we can observe that the estimated values somewhat diverge from manufacture data sheet value at STC. However, for poly-crystalline (KC200GT) is exactly fits the current-voltage curve based on manufacturer product data for proposed three-diode model.

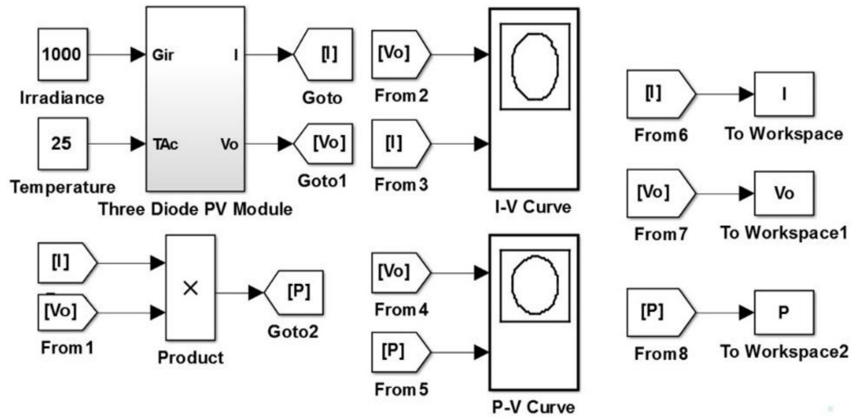

Figure 5: Overall Photovoltaic Model of proposed three diode model

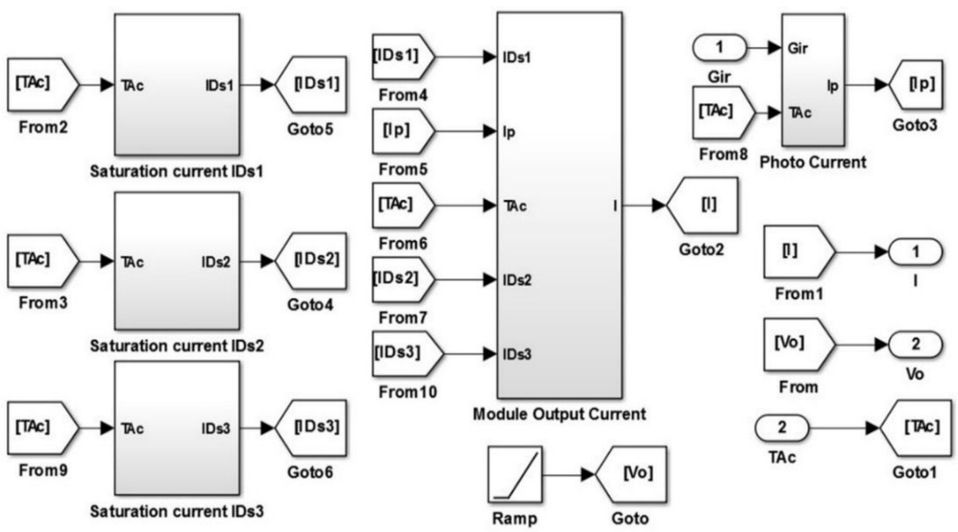

Figure 6: Complete Sub-system Model of proposed three diode photovoltaic cell

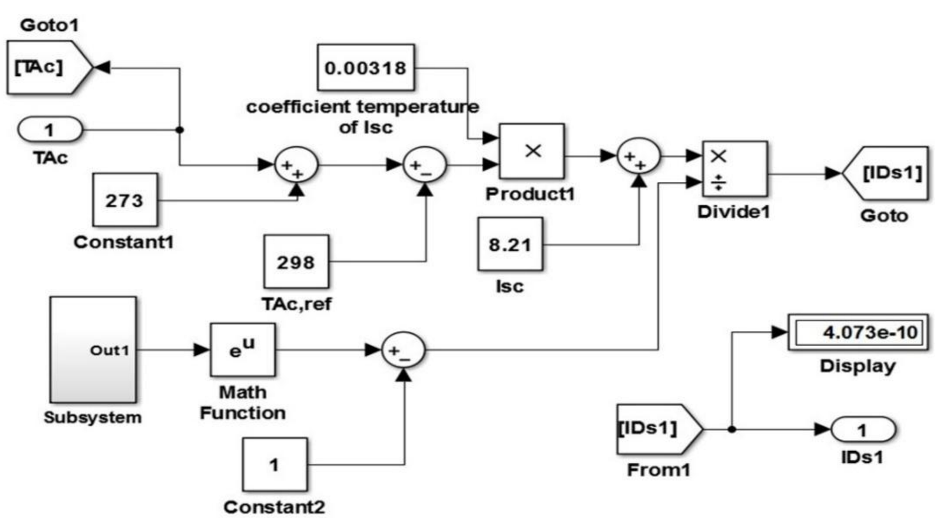

Figure 7: Saturation Current I_{DS} of proposed three diode photovoltaic cell

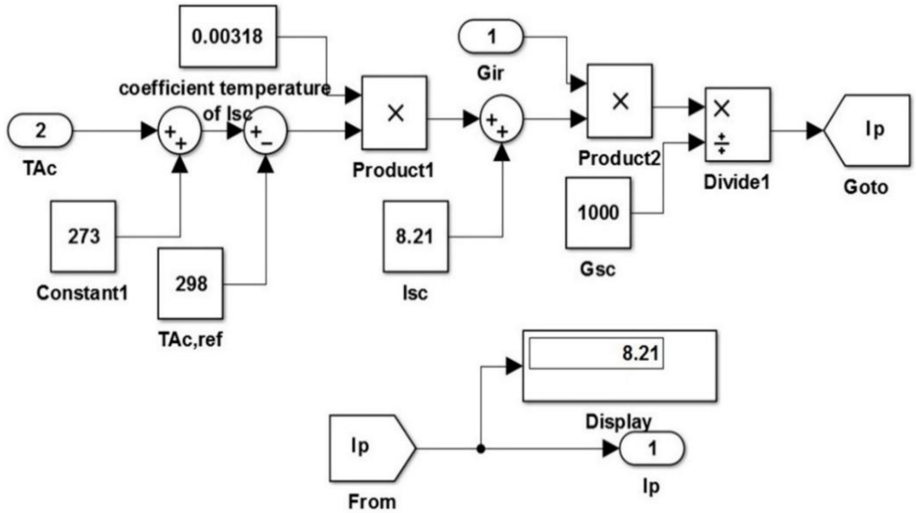

Figure 8: Light Current I_p of proposed three diode photovoltaic cell

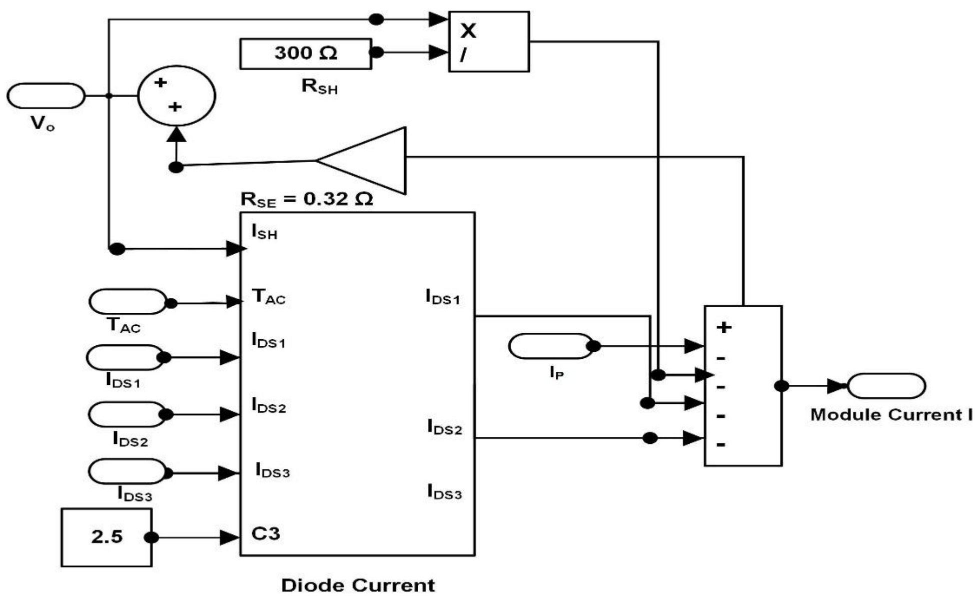

Figure 9: Module Output Current of proposed three diode photovoltaic cell

Table 1: Module Specifications from constructor data sheet

Constraints	Poly-crystalline Kyocera KC200GT Solar Panel [17]	Poly-crystalline Solarex MSX-64 [18]
Maximum Power (P_{mpp})	200 W	64 W
Voltage at P_{mpp} (V_{mpp})	26.3 V	17.5 V
Current at P_{mpp} (I_{mpp})	7.61 A	3.66 A
Voltage at open circuit (V_o)	32.9 V	21.3 V
Current at short circuit (I_{SC})	8.21 A	4 A
Series Connected cell (N_{SE})	54	36
Voltage Temperature coefficient (K_v)	-123 mV/^{0}C	-80 mV/^{0}C
Voltage Temperature coefficient (K_{SC})	0.318 A/^{0}C	0.65 ^{0}C

Table 2: Estimated Values of Proposed Three-diode model

Constraints	**Poly-crystalline Kyocera KC200GT**	**Poly-crystalline Solarex MSX-64**
Maximum Power (P_{mpp})	200.11 W	64.67 W
Voltage at P_{mpp} (V_{mpp})	26.32 V	17.466 V
Current at P_{mpp} (I_{mpp})	7.603 A	3.682 A
Voltage at open circuit (V_o)	32.9 V	21.3 V
Current at short circuit (I_{SC})	8.21 A	4 A
Light Current (I_p)	8.21 A	4.01 A
Saturation Currents ($I_{DS1} = I_{DS2} = I_{DS3}$)	4.073 x 10^{-10} A	3.937 x 10^{-10} A
Diode Ideality Factor (C)	$C_2 = 2.2$, C_3=2.5	$C_2 = 1.3$
Series Resistance (R_{SE})	0.32 Ω	0.3 Ω
Shunt Resistance (R_{SH})	300 Ω	160.4 Ω

Table 3: Estimated Values of Two-diode model

Constraints	**Poly-crystalline Kyocera KC200GT**	**Poly-crystalline Solarex MSX-64**
Maximum Power (P_{mpp})	198.14 W	62.9 W
Voltage at P_{mpp} (V_{mpp})	26.32 V	17.46 V
Current at P_{mpp} (I_{mpp})	7.528 A	3.605 A
Voltage at open circuit (V_o)	32.9 V	21.3 V
Current at short circuit (I_{SC})	8.21 A	4 A
Light Current (I_p)	8.21 A	4.01 A
Saturation Currents ($I_{DS1} = I_{DS2}$)	4.073 x 10^{-8} A	3.937 x 10^{-8} A
Diode Ideality Factor (C)	$C_2 = 2.2$, C_3=2.4	$C_2 = 1.2$
Series Resistance (R_{SE})	0.36 Ω	0.35 Ω
Shunt Resistance (R_{SH})	282.33 Ω	167.25 Ω

Table 4: Comparison of estimated values at maximum power (P_{mpp}) of Three-diode model and Two-diode model for poly-crystalline (KC200GT) solar cell

Constraints	**Manufacturer Data at STC**	**Three-diode model**	**Two-diode Model**	**% Relative Error of Three-diode model**	**% Relative Error of Two-diode model**
Maximum Power (P_{mpp})	200 W	200.11 W	198.14 W	- 0.055	0.93
Voltage at P_{mpp} (V_{mpp})	26.32 V	26.32 V	26.32 V	0.00	0.00
Current at P_{mpp} (I_{mpp})	7.61 A	7.603 A	7.528 A	0.091	1.077
Voltage at open circuit (V_o)	32.9 V	32.9 V	32.9 V	0.00	0.00
Current at short circuit (I_{SC})	8.21 A	8.21 A	8.21 A	0.00	0.00

Table 5: Comparison of estimated values at maximum power (P_{mpp}) of Three-diode model and Two-diode model for polycrystalline solar cell (MSX-64)

Constraints	**Manufacturer Data at STC**	**Three-diode model**	**Two-diode Model**	**% Relative Error of Three-diode model**	**% Relative Error of Two-diode model**
Maximum Power (P_{mpp})	64 W	64.67 W	62.9 W	- 1.04	1.71
Voltage at P_{mpp} (V_{mpp})	17.5 V	17.466 V	17.466 V	0.194	0.194
Current at P_{mpp} (I_{mpp})	3.66 A	3.682 A	3.605 A	- 0.601	1.5
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

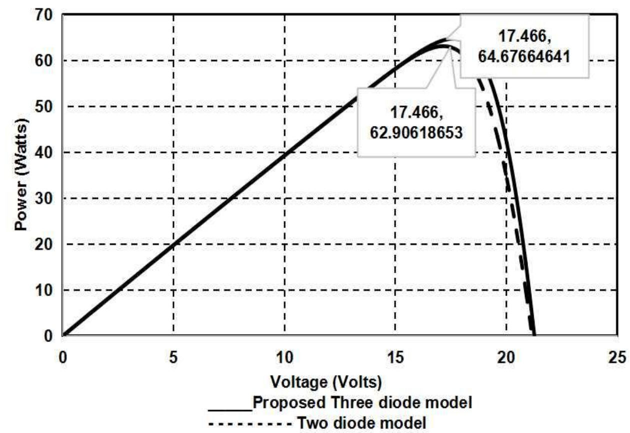

Figure 10: Power (W) Vs Voltage (V) Curve of Proposed Three-diode model and Two-diode model for MSX-64 at STC (25^0 C and 1000 KW/m^2)

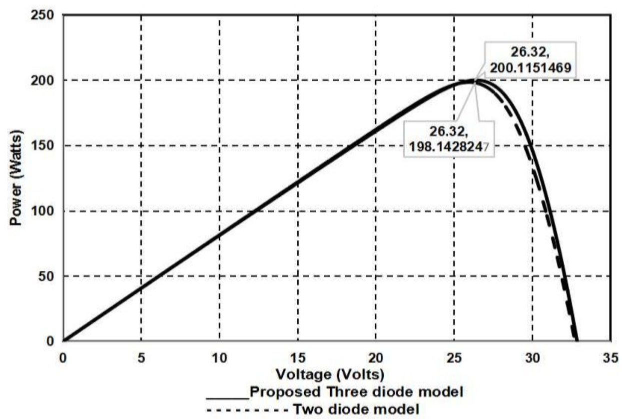

Figure 11: Power (W) Vs Voltage (V) Curve of Proposed Three-diode and Two-diode model for KC200GT at STC (25^0 C and 1000 KW/m^2)

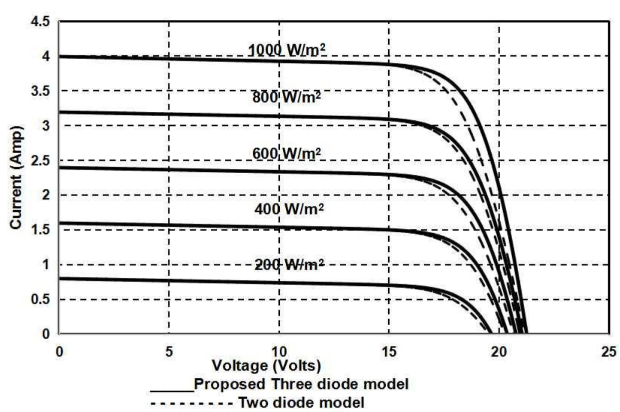

Figure 12: Comparison of Current (A) Vs Voltage (V) Curve of both Proposed Three-diode and Two-diode model for KG200GT with different irradiance at STC (25^0 C)

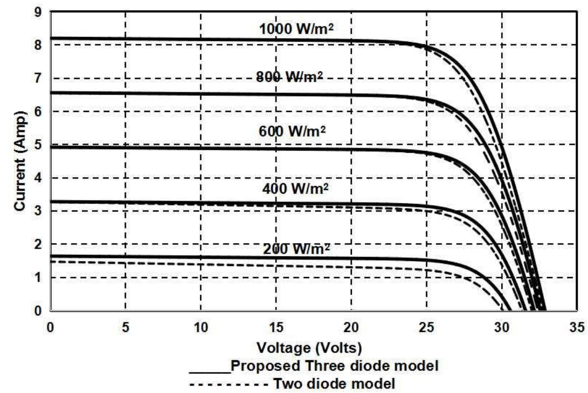

Figure 13: Comparison of Current (A) Vs Voltage (V) Curve of both Proposed Three-diode and Two-diode model for KC200GT with different temperatures at STC (1000 KW/m^2)

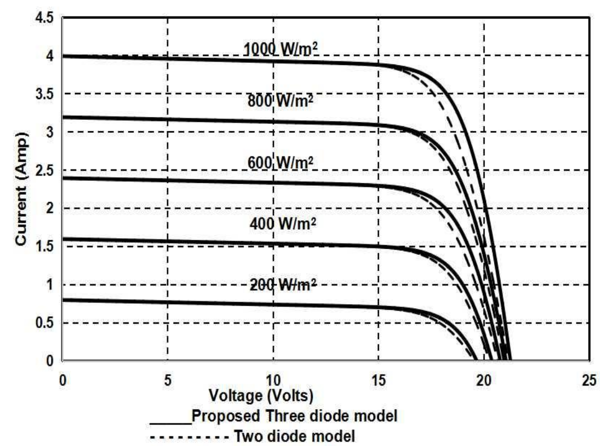

Figure 14: Comparison of Current (A) Vs Voltage (V) Curve of both Proposed Three-diode and Two-diode model for MSX-64 with different irradiance at STC (25^0 C)

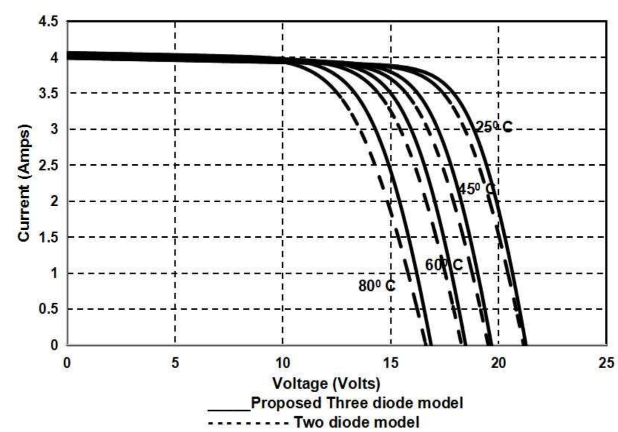

Figure 15: Comparison of Current (A) Vs Voltage (V) Curve of both Proposed Three-diode and Two-diode model for MSX-64 with different temperatures at STC (1000 KW/m^2)

The proposed three-diode model truly requires only five constraints because saturation current $I_{DS1} = I_{DS2} = I_{DS3} = I_{DS}$ whereas $C_1 = 1, C_2 = 2.2,\ C_3$ is chosen greater than 2 [2] and the value of p is recommended to be value larger than 2.2 [1].

Figure10 and Figure 11 signifies the power versus voltage curve of two diode and proposed three-diode model for multi or poly-crystalline solar cell at STC. Comparison of Current versus voltage curves of both two diode and proposed three-diode model for KC200GT solar cell at various temperature and irradiance points are illustrated in Figure 12 and Figure 13. Comparison of Current versus voltage curves of both two diode and proposed three-diode model for poly-crystalline MSX-64 at various temperature and irradiance points are illustrated in Figure 14 and Figure 15. From the obtained outcomes we can witness that both models exhibit the same performance at STC. However, proposed three diode model shows the better performance compared to two diode model precisely at lesser irradiance and higher temperature points especially for open circuit voltage.

6. Conclusion

Developing the mathematical model of photovoltaic (PV) cell, to simulate the module and predict their actual performance at varying temperature and irradiance condition, is very significant for evaluation of photovoltaic cell, as well as for dynamic analysis of dc-dc converters and design of maximum power point algorithms. In this work the general method on modeling of photovoltaic cell module using three diode model is presented. The photovoltaic (PV) cell current-voltage equation formulation is analyzed at three main points specifically at open circuit voltage (V_o) short circuit current (I_{SC}) and maximum power point (P_{mpp}) condition. Distinct to the earlier model presented by some researchers this simplified three diode model needs the calculation of five constraints only. This paper has developed the detailed equations for modelling of three-diode PV module and necessary algorithm for evaluating constraints by effective iteration procedure. The accuracy of the developed model is validated by using experimental data provided by manufacturer's datasheet for two different multi or polycrystalline photovoltaic (PV) modules. The proposed three-diode model have better performance regardless to variations in temperature and irradiance. In specific, this model shows the improved performance and accurateness at lower irradiance and higher temperature situations in comparison with two-diode model especially at the point of open circuit voltage condition.

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