

A Comparative Study of Model Based Design of PV cell in MATLAB/Simulink/Simscape



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Abstract— Solar-electric-energy system has grown consistently over the years. The core of solar power generation system is a solar cell. Modeling the solar cell is required for study of photovoltaic systems. This paper focuses to show different models that simulate the IV and PV performance characteristics of the solar cell and compared. The PV models based on diodes or equation based and models in MATLAB, Simscape are considered. Three, diode based PV cell models of, Open circuit (O/C) voltage & Short Circuit (S/C) current with 5 parameters, Equivalent circuit with 5 and 8 parameters configurations are examined. These solar cell diode based models characteristics are compared with the Solar cell model in MATLAB Simscape, Simelectronics library which is modelled such that the user has a choice to select from one of the three mentioned configurations of PV cell. The comparative studies are validated with the results of Manufacturer datasheet for certain test conditions and parameters. On the basis of all these, the adequate model is selected.

Key words— Solar cell, Simscape, PV cell modeling, parameter based model, Two-diode, Single-diode.

I. INTRODUCTION

The report on annual energy outlook in [1] points out that by 2035; the combined intermittent, non-dispatchable generation sources are expected to deliver 4% of total generation in energy. Impediments to increasing this percentage further stem from (i) the need to install expensive spinning reserves, (ii) the resulting wear and tear of thermal units, and (iii) the inability to achieve adequate voltage [2]. Generations by conventional generator are not being completely replaced by the Renewable Energy Sources (RES) technology, but it is significantly added to balance the demand power requirement in the power system. In connection to the RES technology are the Photo-voltaic (PV), Wind Turbine Generator (WTG), Fuel Cells (FCs), geothermal, and tidal energy systems [3]. Among these the PV power generation is the rapidly developing technology. The evolution of distributed PV is made evident by the 878 MW increase in grid-connected PV capacity in the US in 2010-nearly a 72% rise in capacity from 2009 [4]. The energy from the PV cells is a clean energy, with high reliability and has a long service. [5].

Thus modeling of PV cell is vital for solar energy system. The diode based PV cell modeling has gained considerable attraction due to the graphical interface of software's like

Matlab / Simulink family which assist in simulation of these models. Various researchers have proposed different models for PV cell based on Coding, equation based design in Simulink using single diode and two diode models. Modeling of diode based PV cell can be developed depending upon the parameters involved in the design as shown in Table 1. They can be of the form 3, 4 or 5 element with 4, 5 or 8 parameters respectively involving single or two diodes.

TABLE I. THE ELEMENTS AND PARAMETERS INVOLVED IN THE DESIGN OF PV CELL

3-element or 4-parameter		4-element or 5-parameter		5-element or 8-parameter	
Element	Parameter	Element	Parameter	Element	Parameter
Current source	I_{PH}	Current source	I_{PH}	Current source	I_{PH}
1 Diode	I_D	1 Diode	I_D	2 Diode's	I_{D1}, I_{D2}
	I^*		I^*		I^*
Series Resistance	R_S	Series Resistance	R_S	Series Resistance	R_S
		Shunt Resistance	R_P	Shunt Resistance	R_P

* Output current of the PV cell.

A simple single diode model, with 3 element and 4 parameters based on diode equations, performance has been studied under different solar insolation levels and effect of change in series resistance was observed in [6-8]. The effect of shunt resistance in the equivalent circuit of single diode PV model with 5 parameters is studied under different solar irradiation levels in [9-11]. Later these equation based models are implemented as model based designs using Simscape, Simelectronics library. In Simscape the PV cell is modeled as equivalent circuit with 5/8 parameters (two diode model) defined as Solar cell block. The characteristics of this model are studied in [12-14]. A comparative analysis of PV cell developed in Simscape is compared with the basic (single and two diodes) models of PV cell developed in Simulink [15-17]. But the models taken into consideration for comparative analysis are of different parameters.

In this paper a comparative analysis of diode based PV cell developed in all the three different configurations available in the Solar cell block is done with similar configuration diode based PV cell models implemented in Simulink. The results are compared under Standard Test Conditions (STC) with the reference manufacturer data sheet in order to validate the results.

II. MODELING OF PV CELL

A. Equation Based Design Of PV cell in Simulink:

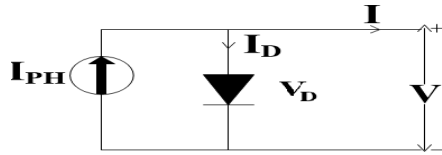


Fig 1: Single diode equivalent of PV Cell

PV arrays are built up by connecting PV solar cells in Series / Parallel combination, which are usually represented by a simplified equivalent circuit model such as one shown in Fig. 1, where voltage across diode is V_D , diode current is I_D , output current from PV cell is represented by I , O/C voltage is V_{oc} or V and S/C current is I_{sc} or I_{ph} . In order to investigate the behavior of a diode based model of PV cell in Matlab, the equivalent circuit parameters are required which are V_{oc} or V , I_{sc} or I_{ph} , V_D , I_D , and I . Additionally Voltage at Maximum Power Point (V_{mpp}), current at maximum power point (I_{mpp}) and maximum power (W_{mpp}) of PV module are also important for modeling. These data are readily available with the PV manufacturer’s datasheet [21].

Equation based modeling of PV cell by O/C Voltage and S/C current, and with Equivalent circuit parameters, and with the implementation of the two models in the MATLAB/Simulink will be discussed in detail in this section.

I. By O/C Voltage and S/C current, 5 parameter Single diode (model A):

The ideal single diode model of PV cell as shown in Fig.1 is a theoretical model. In order to simulate the characteristics of the PV cell similar to the practical PV cell, the single diode model is modified by adding a contact resistance i.e series resistance (R_s), shunt resistance (R_p) as shown in Fig.2.

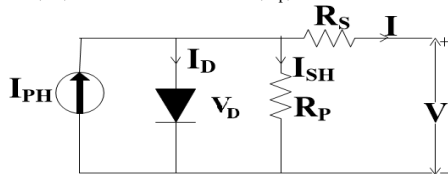


Fig 2: Equivalent circuit of Solar Cell

Fig.2 shows the electrical equivalent circuit of PV cell by O/C voltage and S/C current, 5 parameter single diode model. The parameter involved in modelling are V , I_{sc} , I_D , R_s , R_p [18].

The output voltage of PV cell is a function of the I that is mainly determined by the (1)-(3)

By KCL,

$$I_{sc} - I_D - \frac{V_D}{R_p} - I_{PV} = 0 \tag{1}$$

Diode Characteristic:

$$I_D = I_s \left(e^{\frac{V_D}{V_T}} - 1 \right) \tag{2}$$

KVL:

$$V = V_D - R_s I \tag{3}$$

The values of the Diode saturation current I_s , R_s , and R_p are calculated at maximum power point (MPP).

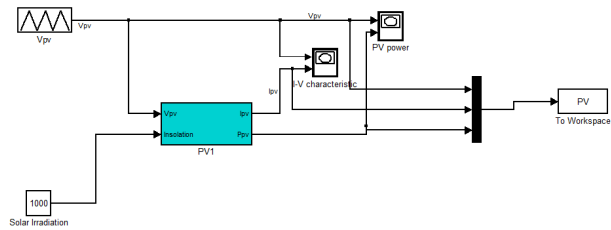
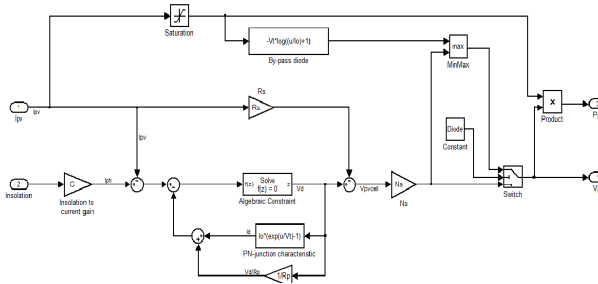


Fig 3: Simulink implementation of model A

Fig. 3 shows Simulink implementation of the PV cell of model A in order to investigate the I-V & P-V characteristics.



The simulated characteristics will be discussed in the following section.

Fig 4: Sub-system of the PV1 module in model A

The “PV1” named block presented in Fig. 3 is the subsystem which is the implementation of (1)-(3) and given in Fig.4. In order to protect the PV cell from hot spots due to non-uniform solar insolation a by-pass diode is included in the design. An option is provided such that the user can select or deselect the by-pass diode into the PV cell model from the promotion window of the PV1. The values of electrical parameters of equivalent circuit are entered from the manufacturer datasheet [21] to simulate the model for the desired output [19].

II. By Equivalent circuit parameters, 5 parameter single diode (model B):

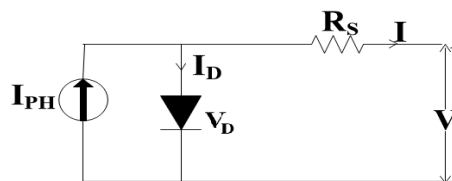


Fig 5: Simplified equivalent circuit of PV cell

The adopted model for Equivalent parameter, 5 parameter single diode model B is shown in Fig.5. It is a 5 parameter single diode model based on V , I_{sc} , I_D , R_s , I in which the shunt resistance is neglected (R_p is infinity) as compared with model A. The output voltage of PV cell is a function of the photocurrent that is mainly determined by the load current depending on the solar irradiation level during operation and is given by (4).

$$V = \frac{A k T_c}{q} \ln \left(\frac{I_{ph} + I_s - I}{I_s} \right) - (I \times R_s) \tag{4}$$

where,

$$k = \text{Boltzmann constant} = 1.38 \times 10^{-23}$$

q = charge on electron = 1.602×10^{-19} C,
 T_c = Reference cell operating temperature, 20°C
 A = curve fitting point.

Both k and T_c should have the same temperature unit, either Kelvin or Celsius. The curve fitting factor A is used to adjust the I-V characteristics of the cell obtained from (4) to the actual characteristics obtained by testing as available in the datasheet. Equation (4) gives the voltage of a single solar cell which is then multiplied by the Number of the cells connected in series to calculate the full array voltage.

If the temperature and solar irradiation levels change, the voltage and current outputs of the PV array will follow this change. Hence, the effects of the changes in temperature and solar irradiation levels should also be included in the PV array model. These effects are represented in the model by the temperature coefficients C_{TV} and C_{TI} for cell output voltage and cell photocurrent, respectively, as:

$$C_{TV} = 1 + \beta_T (T_a - T_x) \tag{5}$$

$$C_{TI} = 1 + \frac{\gamma_T}{S_c} (T_x - T_a) \tag{6}$$

Thus the change in the operating temperature and in the photocurrent due to variation in the solar irradiation level can be expressed via two constants, C_{SV} and C_{SI} , which are the correction factors for changes in cell output voltage V_c and photocurrent I_{ph} , respectively:

$$C_{SV} = 1 + \beta_T \alpha_s (S_x - S_c) \tag{7}$$

$$C_{SI} = 1 + \frac{1}{S_c} (S_x - S_c) \tag{8}$$

S_c , T_a are the benchmark reference of solar irradiation, temperature which can be obtained from datasheet and S_x , T_x are the new level of solar irradiation, temperature. β_T , γ_T , α_s are the temperature co-efficient of voltage, current, power respectively these values can be obtained from the datasheet [21].

The new values of the PV cell output voltage (V_c) and the output current I_{phx} with the new solar irradiation S_x and temperature T_x is:

$$V_{cx} = C_{TV} \times C_{SV} \times V_c \tag{9}$$

$$I_{phx} = C_{TI} \times C_{SI} \times I_{ph} \tag{10}$$

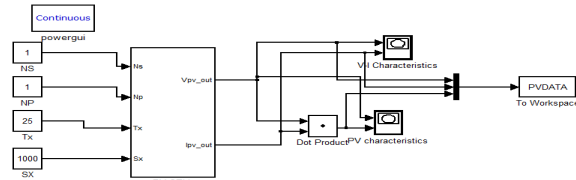


Fig 6: Simulink implementation of PV cell model B

Fig. 6 shows the Simulink implementation of single diode PV cell by equivalent circuit, 5 parameter model B.

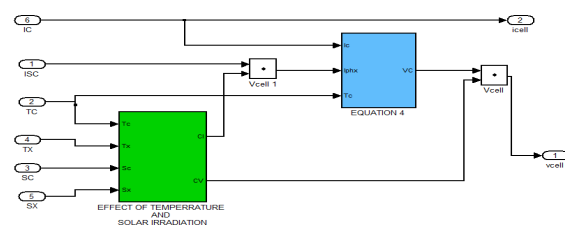


Fig 7: Sub-system of PV cell block in the model B

The PV cell block in Fig. 6 is the sub syetm implementation as shown in Fig.7. Equation (4) block in Fig.7 is the Simulink implementation of (4) as a sub-system and (5)–(8) are implemented in Simulink as a sub-system which represents the effect of change in temperature and solar irradiation as a block in Fig.7. The Fig.7 also shows the Simulink implementation of (9), (10) [20].

The I-V characteristics and P-V characteristics of the model B obtained from simulation will be discussed in the following section.

III. By Equivalent circuit parameters, 8 parameter two diode (model C) :

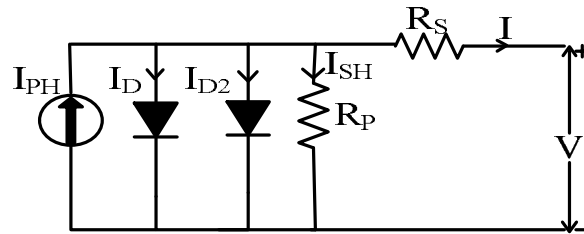


Fig 8: Model of Two-diode equivalent of PV cell

The Electrical equivalent circuit of the PV cell by Equivalent circuit parameters, 8 parameter two diode model C is shown in Fig. 8. It is a 8 parameter two diode model based on V_c , I_{D1} , I_{D2} , R_{s1} , R_{p1} , I , N_1 , N_2 . The modelling as discussed in [13].

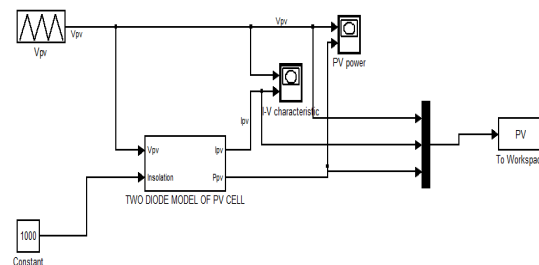


Fig 9: Simulink implementation of PV model C

The Simulink implementation of PV cell model C is shown in Fig. 9. The I-V & P-V characteristics of PV cell model obtained from simulation will be discussed in the following section.

In the following section model based design of PV cell using Solar cell block available in the Simelectronics library as a source implemented in the Simulink, Simscape will be discussed.

III. Model Based Design Of PV Cell In Simulink, Simscape:

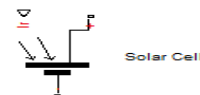


Fig 10: Solar Cell Block in Simscape/Simelectronics

A solar cell as an energy source is available in the Simscape, simelectronics library as shown in Fig. 10. The equivalent circuit of the solar cell block is similar to that represented in Fig. 8. The output current of the equivalent circuit of the solar cell as shown in Fig. 8 is given by (10).

$$I = I_{ph} - I_s \left[e^{\left(\frac{V + R_s \times I}{N \times V_t} \right)} - 1 \right] - I_{s2} \left[e^{\left(\frac{V + R_s \times I}{N_2 \times V_t} \right)} - 1 \right] - \frac{V + R_s \times I}{R_p} \quad (10)$$

The solar cell block shown in Fig. 8 has different configurations which allows the user to select appropriate model as explained below:

I. *By O/C Voltage and S/C current, 5 parameter single diode (model D):*

On selecting this option the equivalent circuit of solar cell as in Fig. 8 converts into the equivalent circuit shown in Fig.2. It provides O/C voltage and S/C current parameters and I_{s2} becomes zero. There by the output current of the equivalent circuit changes from (10) to (1).

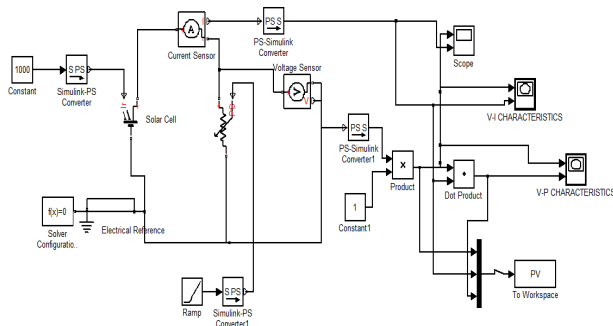


Fig 11: Solar cell Model in the Simulink

A simple circuit is being implemented as shown in Fig.11 where a variable resistance is connected across the solar cell. Using a unit ramp signal the value of resistance is varied from zero to maximum value in order to create O/C and S/C condition at the terminals of the solar cell by which the characteristics of the solar cell can be plotted. In order to plot the characteristics of PV cell model D the parameters V_{oc} , I_{sc} , R_s , N , I_s , Irradiance used for measurement are entered from datasheet [21] in the solar cell and simulated.

The I-V characteristics and P-V characteristics of the model D obtained from the simulation will be discussed in the following section.

II. *By Equivalent circuit parameters, 5 parameter single diode (model E):*

By selecting the configuration it provides electrical parameters of an equivalent circuit model of a solar cell as shown in Fig. 5. By selecting this model the parameters I_{s2} becomes zero and the value of R_p is infinity. There by the output voltage of the PV cell model E is given by (4). The simulink implementation of PV cell model E is similar to that shown in Fig. 10. From the block parameters of solar cell the configuration "By Equivalent circuit parameters, 5 parameter" is selected and the I-V & P-V characteristics are simulated by entering the values of parameters of I_s , I_{PH} , N , R_s , Irradiance from datasheet [21].

Thus I-V and P-V characteristics of the model E obtained from simulation will be discussed in the following section.

III. *By Equivalent circuit parameters, 8 parameter two diode model F:*

By selecting the configuration it provides the electrical parameters of the equivalent circuit of the solar cell as shown in Fig. 8. The output current of the PV cell model F is given by (10). In order to simulate the characteristics of the PV cell model F a simple circuit is implemented as shown in Fig.10. by choosing this configuration from the block parameters of solar cell block and parameters such as I_s , I_{s2} , I_{PH} , N , N_2 , R_s , R_p , Irradiance are inputted into the solar cell block obtained from datasheet [21]. The model is simulated and the characteristics are plotted.

The I-V and P-V characteristics of the model F obtained from simulation will be discussed in the following section.

IV. SUNPOWER A-300 SOLAR CELL, MONO CRYSTALLINE SILICON DATASHEET [21]:

I-V characteristic of the reference solar cell from the datasheet [21] is shown in Fig.12. The electrical parameters of the reference PV cell are shown in Table.II.

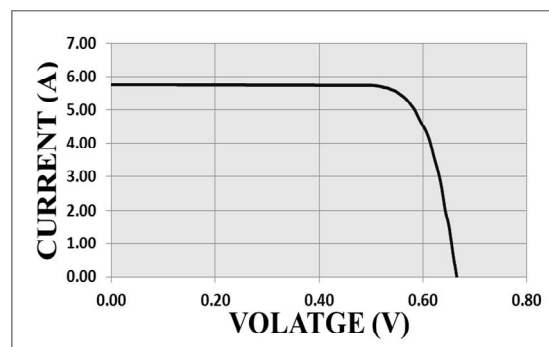


Fig 12: I-V characteristics of Sun power A-300

TABLE II. SUNPOWER A-300 DATASHEET

Open Circuit Voltage	0.665 V	Maximum Power Current	5.35 A
Short Circuit Current	5.75 A	Rated Power	3.0 W
Maximum Power Voltage	0.560 V	Efficiency	20.0% minimum
Temperature Coefficients			
Voltage	-1.9 mV / 0C		
Power	-0.38% / 0C		

These values from Table II are substituted in the simulation models and simulated in order to obtain the characteristics similar to that shown in Fig. 12. In the following section validation study is done by comparing the obtained simulated results with the Sun power A-300 solar cell characteristics and electrical parameters from the manufacturer datasheet.

V. ANALYSIS OF PV MODELS

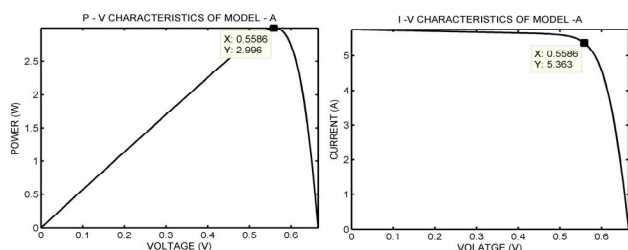


Fig 13: P-V & I-V Characteristics of Model-A (Simulink)

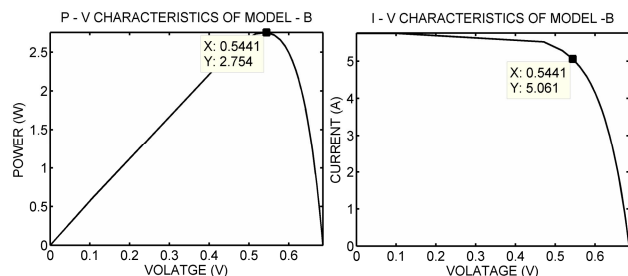


Fig 14: P-V & I-V Characteristics of Model-B (Simulink)

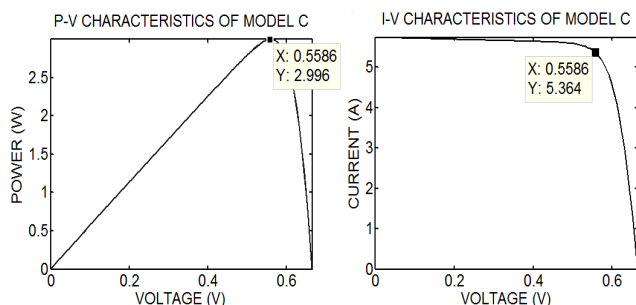


Fig 15: P-V & I-V Characteristics of Model-C (Simulink)

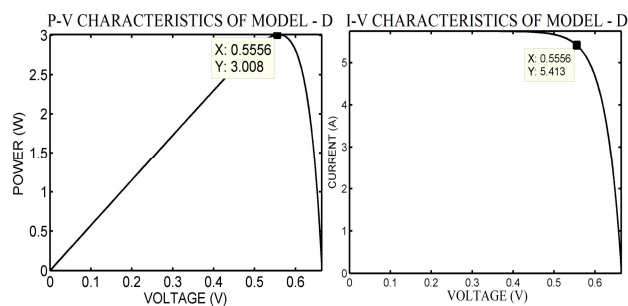


Fig 16: P-V & I-V Characteristics of Model-D (Simscape)

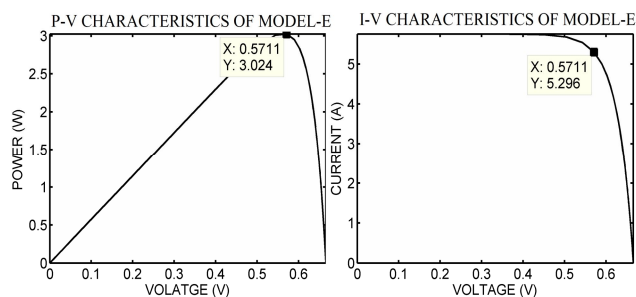


Fig 17: P-V & I-V Characteristics of Model-E (Simscape)

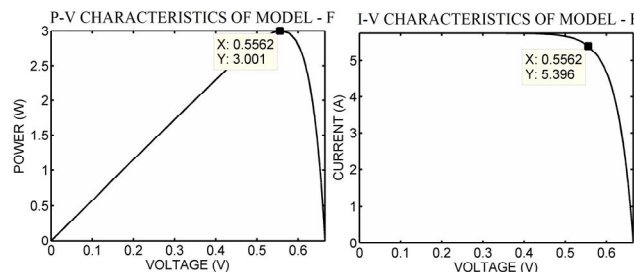


Fig 18: P-V & I-V Characteristics of Model-F (Simscape)

Fig. 13-18 shows the simulated output characteristics of models developed in MATLAB/ Simulink and Simscape. The values of V_{mpp} , I_{mpp} , W_{mpp} are marked in the respective simulated characteristics. The electrical parameters of diode based PV cell developed in simulink , diode based PV cell developed in Simscape, the manufacturer data sheet at STC are shown in table III for comparison.

The I-V characteristics of the equation based design of diode based PV cell models (A, B and C) in simulink i.e Fig. 13, 14, 15 respectively are compared with the characteristics of reference or Datasheet [21] i.e Fig.12. The I-V characteristics of model- A & C are closer to the reference characteristic. Now comparing the electrical parameters considering the output power W_{mpp} of the model A, B, C with the output power W_{mpp} of the data sheet i.e 3.0 W. From the Table III it is clear that the Model A & C produce similar output power W_{mpp} i.e. 2.9958 W.

Now comparing the I-V characteristics of the model based design of diode based PV cell (model D, E and F) in Simulink, simscape i.e. Fig. 16, 17, 18 respectively with the Manufacturer data sheet I-V characteristic i.e. Fig.12. it is observed that the I-V characteristics of the model D, E, F are similar to that of I-V characteristic of Manufacturer data sheet. Comparing the electrical parameters of the models considering the W_{mpp} i.e. 3.0 W from the data sheet as shown in Table.III, it is clear that model D, E, F produces W_{mpp} nearer to 3.0 W. The accurate one among model D, E, F is the model F i.e. 3.0013W.

It is also observed that the voltage V_{oc} of the model A, C & F matches exactly with the data sheet i.e. 0.665V. The I_{sc} of all the models matches exactly with the reference model i.e. 5.75A. The W_{mpp} of the model A, C, D, E, F are similar to that of reference model but Model F has much closer value i.e. 3.0013 W. Similarly comparing V_{mpp} , I_{mpp} of the model the model F has similar results.

From the study it is clear that the Simulink, simscape implementation of PV cell by Equivalent circuit, 8 parameter model F produces more similar results to that of manufacturer datasheet. Simulink modelling of diode based PV cell using solar cell available in the Simscape, simelectronics library is easy as compared with the equation based modelling of PV cell models A, C. Henceforth we can conclude that the PV cell model F produces accurate characteristics similar to that of data sheet.

TABLE III.

SIMULATION RESULTS IN MATLAB/SIMULINK/SIMSCAPE

CHARACTERISTICS	DATASHEET	SIMULINK MODELS			SIMSCAPE/SIMELEC TRONICS MODEL		
	SUNPOWER A-300	MODEL - A	MODEL - B	MODEL - C	MODEL - D	MODEL - E	MODEL - F
Voc (V)	0.665	0.665	0.6857	0.665	0.6641	0.6654	0.665
Isc (A)	5.75	5.75	5.752	5.7434	5.75	5.75	5.75
Wmp (W)	3.0	2.9958	2.7532	2.9958	3.0078	3.0242	3.0013
Vmpp (V)	0.560	0.5586	0.5440	0.5586	0.5556	0.5711	0.5562
Imp (A)	5.35	5.3631	5.0609	5.3631	5.4135	5.2957	5.3961
Irradiation (W/m ²)	1000	1000	1000	1000	1000	1000	1000
TEMP. (°C)	25	25	25	25	25	25	25

VI. CONCLUSION

The main objective of the paper is to investigate three different diode based PV cell model implemented in Simulink and Simscape and compare the simulated characteristic with the manufacturer data sheet characteristics.

Model precision depends on the parameters calculation from the manufacturer data sheet and also by considering the effect of change in solar irradiation levels and cell operating temperature. The solar cell models considered are diode based model of PV cell modeled by O/C Voltage & S/C current, 5 parameter single diode model, Equivalent circuit, 5 & 8 parameters single & two diode model.

It is observed that the diode based model of PV cell by "Equivalent circuit, 8 parameter two diode" implemented by solar cell from Simscape, Simelectronics library produced the output characteristics similar to that of data sheet. There by this model can be used as an accurate PV model for further study.

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