

An Accurate Modeling of Photovoltaic System for Uniform and Non-Uniform Irradiance

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Abstract- Efficient modeling and simulation of photovoltaic (PV) systems has become more important due to the wide integration of solar energy in modern power systems. The equations describing the PV systems are transcendental nonlinear in nature, this results a slow and inefficient simulations for long-term analysis. This paper proposes a modified approach of modeling photovoltaic array for uniform and non-uniform irradiance condition. Initially for uniform irradiance condition single diode model is used as equivalent circuit. A method based on adaptively varying the value of series resistance is proposed to find the equivalent circuit parameters. The proposed model is simulated using MATLAB and results are validated using the experimental results obtained from the datasheet values and other models in the literature. The model is extended for non-uniform irradiance and the results are validated. The proposed methodology found to have advantage over the other conventional methods in terms of accuracy and less simulation time.

Keywords- Modeling, uniform irradiance, non-uniform irradiance, photovoltaic (PV) array

1. Introduction

Photovoltaic energy systems have become a key area of research in the recent times. The output of PV module mainly depends on solar irradiance and module temperature. There are many mathematical models in the literature for obtaining the characteristics of photovoltaic module. The mathematical model is expressed in terms of equivalent circuit. The parameters of the equivalent circuits are light generated current (I_{ph}), diode reverse saturation current (I_0), series resistance (R_s), shunt resistance (R_p) and diode ideality factor (a). All these parameters are calculated using the values available in PV datasheet [1].

The simplest equivalent circuit is the ideal diode model in which the current source is connected anti-parallel to diode [2]. This model does not give accurate results. An improvement to this model is presented in [3] in which a series resistance is added to the equivalent circuit. In this method a data based approach is implemented using look-up table. The values of (R_s and a) are varied at that particular temperature until the maximum power condition is minimized to a pre-specified tolerance limit. With the obtained values of a and R_s for different temperatures two look up tables (T vs. R_s) and (T vs. a) are formed. Since the parallel resistance is neglected, less

accurate results are obtained at different irradiance and temperature conditions.

Further improvement is made by adding a parallel resistance to the equivalent circuits as in [1], [4] and [5]. The authors in [4] proposed a single diode model in which the three parameters a , R_s , R_p are obtained by solving non-linear equations iteratively using numerical algorithms. A similar method is presented in [6] in which the three parameters are calculated iteratively using gauss seidal method. As non-linear equations are solved iteratively, it leads to huge computational burden.

The authors in [1] proposed power matching algorithm to find the value of series resistance and shunt resistance. Even though this model is simple and accurate method of finding the values of R_s and R_p , but this model neglected the value of diode current in finding the value of light generated current (I_{ph}).

A two diode model is implemented in [6] which is extension of single diode model in [1]. The value of R_s and R_p are calculated in similar procedure to [1]. The reverse saturation current of both the diodes considered same. The diode ideality factors are calculated according to Schokley diffusion theory. Compared to single diode model, this model is complex. In order to overcome the drawbacks of existing models, a single diode model is presented in this paper. The proposed model takes the advantages of [1] and [4]. The value of shunt

resistance and series resistance are calculated using [1] and the value of I_{ph} and I_o are calculated according to [4]. Apart from this, the proposed model is improved by adaptively varying the value of series resistance in order to decrease the computational time.

If PV array is subjected to conditions like shadows, clouds, dirt, debris and bird droppings etc., then condition of non-uniform irradiance occurs. If several solar cells in a series PV module are mismatched due to non-uniform irradiance, these cells will limit the output current of normal cells. This leads to decrease of the output power, and hot spots may be generated that leads to damage of the cell. In order to avoid the destructive effects of hotspot, a bypass diode is connected in parallel with a PV module or in parallel with some series-connected solar cells in a PV module, which creates an alternative path for module current. The output power of mismatched cells is cut off when the bypass diode works [8].

The authors in [8] developed a MATLAB model for simulating the non-uniform irradiance conditions which is an extension of the work in [7]. The authors in [7] used an R_s model. The value of light generated current is approximated to short circuit current. The model is developed on MATLAB-Simulink using S-function builder and controlled current source. But R_s model exhibits inaccuracy at temperature variations.

The two diode model presented in [9] is extension of work done in [6] in which a linear interpolation with extrapolation techniques is used to find the I - V and P - V characteristics under non-uniform irradiance conditions. Since linear interpolation technique is used, it leads to inaccuracy. Also the implementation complexity is more for a two diode model.

An analytical model with single diode model of mismatched PV fields by means of Lambert-W function is presented in [10] with detailed model of bypass and blocking diode. The output current is expressed explicitly as a function of voltage using Lambert-W function and is expressed as a matrix and solved by expressing the string current in the form of Jacobian matrix. Although this method is accurate it is highly complex and takes long implementation time.

A simplified version of [10] is in presented [11] by neglecting series and shunt resistances, and bypass diode is modeled as an ideal switch. The model is simple and less accurate and is used for predicting the PV array performance under non-uniform irradiance conditions for a long term evaluations of energy on a daily, monthly and yearly basis.

A trade-off model that comprises the advantages of [10] and [11] is proposed in [12]. A single diode model is considered with blocking and bypass diodes considered as piecewise linear models. Output voltage is expressed as an explicit function of current using Lambert-W function. Unlike [10] and [11] no matrix is used. The entire set of PV voltages of modules that are

connected in a string are expressed in a single equation which is a summation of expressions for voltage of active modules, voltage of inactive modules (bypass diodes) and voltage of blocking diodes. Once the expression of string voltage is obtained, Newton Raphson method is used to obtain the value of string current. Because of these advantages, the algorithm in [12] is used for extending the proposed model to non-uniform irradiance conditions in this paper.

This paper is organized as follows: section 2 presents modeling under uniform irradiance conditions. Section 3 presents modeling under non-uniform irradiance conditions. Section 4 presents the results and discussions. Concluding remarks are presented in section 5.

2. Modeling Under Uniform Irradiance

A single diode model depicted in fig. 1 is considered for modeling PV system under uniform irradiance conditions.

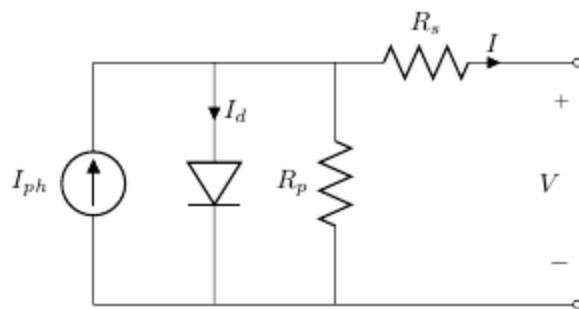


Fig. 1. Single Diode Model

By applying KCL to fig. 1, equation (1) is obtained.

$$I = I_{ph} - I_o \left[\exp \left(\frac{q(V + IR_s)}{akTN_s} \right) - 1 \right] - \frac{V + IR_s}{R_p} \quad (1)$$

Where

- I_{ph} light generated current of PV module in Amperes
- I_o reverse saturation current in Amperes
- R_s series resistance in Ohms
- R_p parallel resistance in Ohms
- a Diode ideality factor
- k Boltzmann constant (1.38×10^{-23} J/K)
- q electron charge (1.6×10^{-19} C)
- N_s number of series connected cells in a module
- T module temperature in Kelvin
- I output current of PV module in Amperes
- V output voltage of PV module in Volts

The equations of the solar PV equivalent circuit are represented in two different operating conditions viz., open circuit condition (OCC) and short circuit condition (SCC). The expressions for open circuit voltage is obtained by substituting output current, $I=0$ and short circuit current is obtained by substituting output voltage, $V=0$ in the equation (1). The

equations for these conditions are expressed in equations (2) and (3).

$$0 = I_{ph} - I_o \left\{ \exp \left(\frac{qV_{oc}}{akTN_s} \right) - 1 \right\} - \frac{V_{oc}}{R_p} \quad (2)$$

$$I_{sc} = I_{ph} - I_o \left\{ \exp \left(\frac{qI_{sc}R_s}{akTN_s} \right) - 1 \right\} - \frac{I_{sc}R_s}{R_p} \quad (3)$$

2.1 Calculation of R_s and R_p

The values of Series Resistance (R_s) and Shunt Resistance (R_p) are extracted in an iterative manner. The value of R_s is incremented starting from an initial value. By incrementing the value of R_s , the corresponding value of R_p is found using equation (4), until $P_{max,e} = P_{max,m}$. The value of R_p is obtained by equating the maximum experimental power ($P_{max,e}$) obtained from datasheet and maximum power obtained from simulation ($P_{max,m}$) from the model [1].

$$R_p = \frac{V_{mp}(V_{mp} + I_{mp}R_s)}{V_{mp}I_{mp} - V_{mp}I_o \exp \left(\frac{q(V_{mp} + I_{mp}R_s)}{akTN_s} \right) + V_{mp}I_o - P_{max,e}} \quad (4)$$

where V_{mp} and I_{mp} are voltage and current at maximum power point. The initial value of series resistance is zero and Shunt Resistance is given as shown in equation (5) [1].

$$R_{pmin} = \frac{V_{mp}}{I_{scn} - I_{mp}} - \frac{V_{ocn} - V_{mp}}{I_{mp}} \quad (5)$$

The value of a that best fits the experimental data specified by the manufacturer is chosen arbitrarily and the value of it is varies between 1 and 2 [1].

2.2 Calculation of I_{ph} and I_o

With the obtained values of series resistance (R_s), Shunt Resistance (R_p) and diode ideality factor (a) values of photovoltaic current (I_{ph}) and reverse saturation current (I_o) are obtained from equations (2) and (3).

2.3 Temperature and Irradiance Dependence

The open circuit voltage (V_{oc}), short circuit current (I_{sc}), light generated current, vary with the change in irradiance and temperature conditions. The light generated current depends on the temperature and irradiance is given by equations (6).

$$I_{ph} = (I_{phn} + K_I dT) \frac{G}{G_n} \quad (6)$$

I_{phn} is the photovoltaic current at standard test condition (STC). dT is difference between the operating temperature (T)

and temperature at STC (T_n). G_n is irradiance at STC. The effect of temperature and irradiance on short circuit current and the effect of temperature on open circuit voltage is given by equation (7) and (8) respectively [4].

$$I_{sc} = (I_{scn} + K_I dT) \frac{G}{G_n} \quad (7)$$

$$V_{oc} = (V_{ocn} + K_V dT) \quad (8)$$

The effect of irradiance on open circuit voltage is obtained by substituting the values of I_{sc} , I_{ph} in equation (2) and then solving for open circuit voltage. K_V and K_I are voltage and current temperature coefficients respectively.

2.4 Special Case

The proposed algorithm is improved by adaptively incrementing the value of series resistance instead of fixed increment. Two special cases are investigated for need of proposed model.

Case 1: PV module datasheet SW235 [15] whose specification is mentioned in table 1 is considered. In the process of finding the equivalent circuit parameters the values of R_s has to be incremented according to the algorithm in [1]. If the value of R_s is incremented in a fixed manner, say $R_{sinc}=0.1$, then R_p may become negative for some particular value of R_s . For example if $R_s=0.3\Omega$, the corresponding value of R_p computed from equation (5) is 270.7815 Ω . For $R_s=0.4\Omega$, the value of R_p is -203.2725 Ω . But the value of R_p should not be negative which implies that the actual value of R_s should lie below 0.4 Ω . In order to overcome this problem, an adaptive method of varying series resistance is proposed.

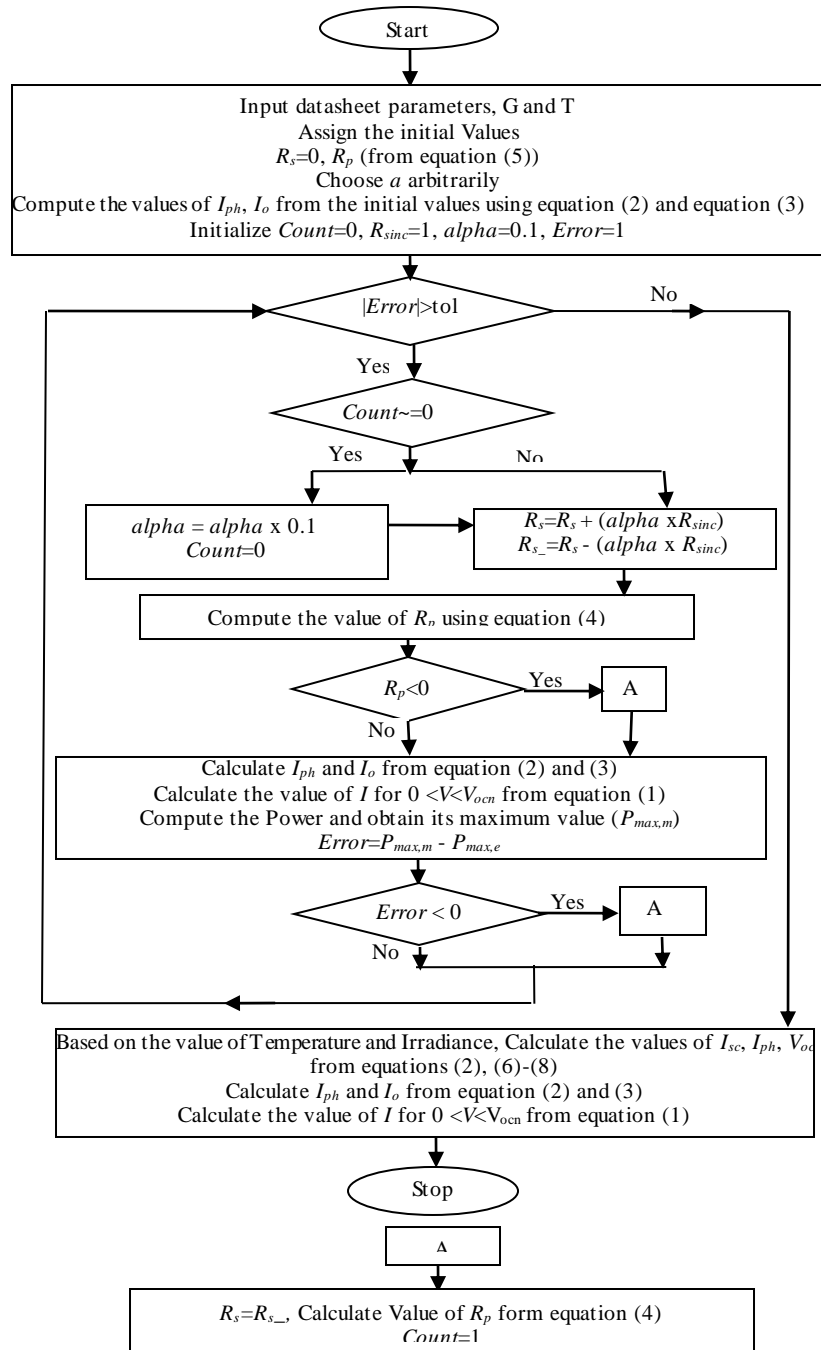
1. Initially the value of series resistance to be incremented, R_{sinc} is assigned 1 and the value of α is assigned 0.1. The value of $count$ is assigned 0.
2. In the process of incrementing the value of R_s if the corresponding value of R_p becomes negative, then R_s will be reverted back to its previous value and $count$ is initialized as 1. In the next iteration the value of α will be multiplied by 0.01 so that the value R_s will be incremented by 0.01. This process continues until the absolute error (difference between simulated maximum power and datasheet maximum power) is within the tolerance limit.

Case 2: PV module datasheet SP-70 [14] whose specifications that are mentioned in table 1 is considered. Similar to the previous case an increment is R_s by 0.1 Ω is considered. In the process of iteration, at $R_s=0.4\Omega$, the corresponding value of R_p , $P_{max,m}$, absolute error are calculated according to the algorithm in [1]. The error at $R_s=0.4\Omega$ which is the difference between $P_{max,m}$ and $P_{max,e}$ is positive and at $R_s=0.5\Omega$, the error becomes

negative. This implies that the maximum power is obtained between the R_s value of 0.4 Ω and 0.5 Ω . Whenever the sign of error is changing from positive to negative, the value of simulated maximum power is less than the datasheet maximum power. If the iteration is continued in the similar manner, then error will further increase with a negative sign leading to divergence of algorithm. This means that the value of R_s should lie between 0.4 and 0.5. So the procedure followed in case 1 i.e. adaptively varying the value of series resistance is used. It is to be noted that the value of error in this case is not absolute error. The entire algorithm is presented in figure 2.

3. Modeling Under Non-Uniform Irradiance

The authors in [12] used the model presented in [1] for modeling non-uniform irradiance. But the proposed model is more accurate than [1]. So the model proposed for uniform irradiance is extended for non-uniform irradiance using the algorithm presented in [12]. The authors in this paper did not specify the type of blocking and bypass diode used. In this paper, Schottky diode is used because of the advantages like low forward voltage drop (0.15-0.45V). The flow chart of the non-uniform irradiance model is presented in fig. 3.



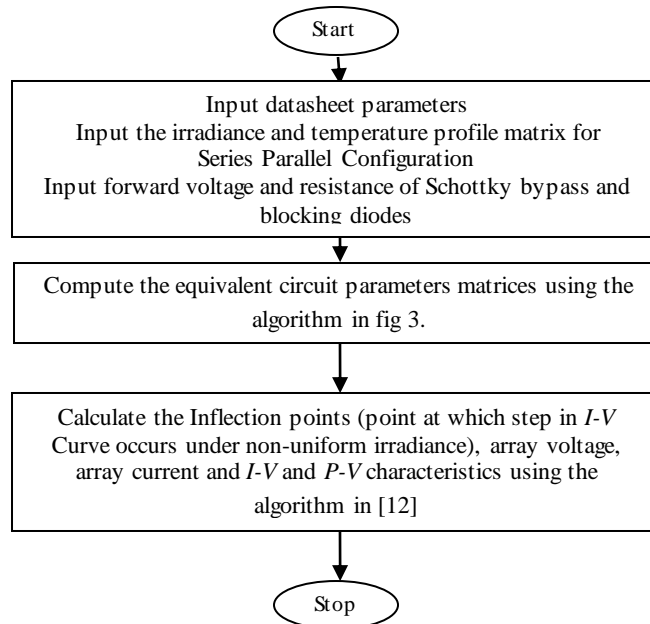


Fig 3. Flowchart for Non-Uniform Irradiance

4. Results and Discussion

The models presented in section 2 for uniform irradiance and section 3 for non-uniform irradiance is validated in this section.

4.1 Validation of Single Diode Model under Uniform Irradiance Conditions

The proposed model is validated using different PV module manufactures datasheets and the experimental results extracted from them. The specifications of various PV module datasheet

values are summarized in table 1. The equivalent circuit parameters of single diode model viz., light generated current or photovoltaic current (I_{ph}), diode reverse saturation current (I_o), series resistance (R_s), parallel Resistance (R_p), diode ideality factor (a) of the modules mentioned in table 1 are calculated based on the proposed algorithm and presented in table 2. The modules KC200GT [13], SP-70 [14], ST-40 [14], SW 235 [15] are used for validation of proposed model in uniform irradiance conditions. SM –55 module [16] is used for validation of proposed model in non-uniform irradiance conditions.

Table 1. Datasheet Parameters

	KC200 GT	SP70	ST40	SW 235	SM 55
I_{scn} (A)	8.21	4.7	2.68	8.35	3.45
V_{ocn} (V)	32.9	21.4	23.3	37	21.7
I_{mp} (A)	7.61	4.25	2.41	7.85	3.15
V_{mp} (V)	26.3	16.5	16.6	30	17.4
K_v (V/ °C)	-0.123	-0.076	-0.1	-0.1258	-0.077
K_I (mA/ °C)	3.18	2	0.35	2.839	1.2
N_s	54	36	36	60	36

Table 2. Parameters of Proposed Single Diode Model

	KC200GT	SP70	ST40	SW 235	SM 55
I_{sc} (A)	8.21	4.7	2.68	8.35	3.45
V_{oc} (V)	32.9	21.4	23.3	37	21.7
I_{pv} (A)	8.213	4.7256	2.70	8.354	3.455
I_o (A)	1.5×10^{-7}	1.5×10^{-9}	2.9×10^{-10}	9.8×10^{-10}	4.8×10^{-8}
R_s (Ω)	0.22	0.5	1.66	0.29	0.3297
R_p (Ω)	649.5	93.25	192.5	570.1	224.424
A	1.3	1.1	1.1	1.05	1.3

The proposed algorithm reduces the execution time by adaptively changing the value of series. The series resistance is generally incremented by a constant value in literature. Instead if series resistance is incremented in an adaptive manner as in Fig. 3 there can significantly decrease in the execution time.

Table 3 compares the execution time when series resistance is incremented with constant value and when the series resistance is incremented adaptively. In all the cases, the execution time of the proposed model is less than the other conventional models in the literature.

Table 3. Comparison of execution time in seconds

Datasheet	Existing Model (sec)	Proposed model (sec)
SM 55	5.827	0.3541
SP_70	5.353	0.328
ST_40	15.569	0.6877
Sun Power SW_235	8.135	0.471
KC200GT	3.8526	0.426

Fig. 4 shows the I - V Curve of KC200GT module at various levels of irradiance (From $G=1000 \text{ W/m}^2$ to 200 W/m^2) with a variation of 200 W/m^2 . The value of module temperature is taken as 25°C . The curves are plotted for the R_s -model, proposed single diode model and the experimental values extracted from datasheet. The proposed model and R_s model

exhibit similar results at standard test conditions because both the algorithms are based on maximum power matching. But when irradiance level decreases the proposed model matches the experimental values i.e., the proposed model is more accurate than single diode model.

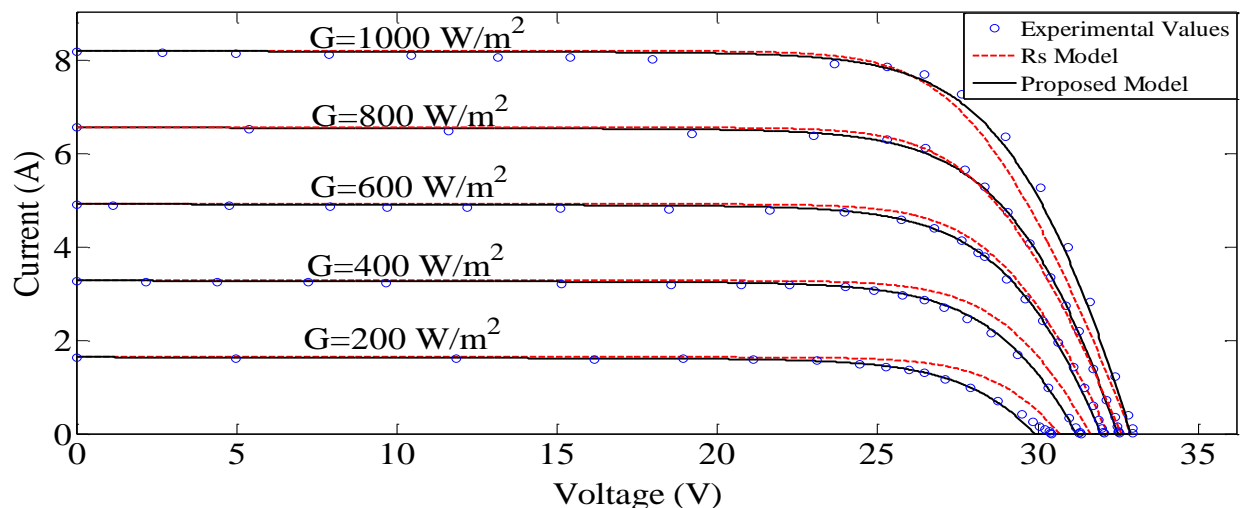


Fig. 4. I-V Curve of KC200GT Module for different shading Conditions

Fig. 5 shows the I - V curve of KC200GT curve at various temperatures (varying from $T=25^{\circ}\text{C}$ to $T=75^{\circ}\text{C}$) with a variation of 25°C . The value of irradiance is taken as 1000 W/m^2 . The values of R_s model and the proposed model remain

same as mentioned in the previous paragraph at standard test condition. At temperatures other than STC the proposed model matches more accurately with the experimental values extracted from datasheet than the characteristics of R_s model.

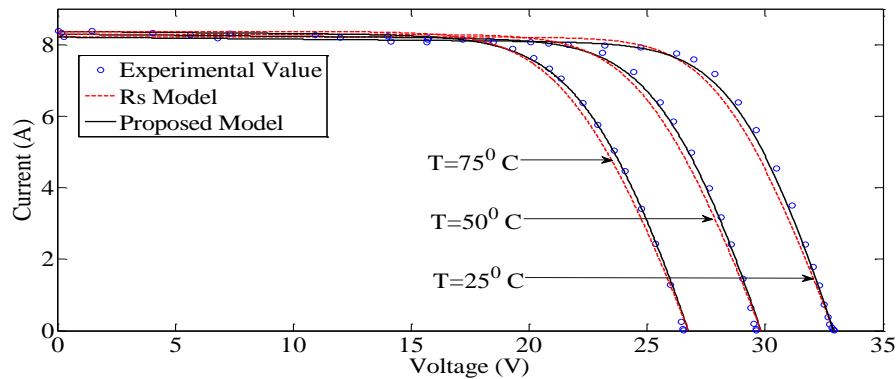


Fig. 5. I - V Curve of KC200GT Module for different Temperature Conditions

The absolute error of current with respect datasheet value at STC is presented in fig. 6. It can be noticed that the proposed

model is giving better results than R_s model especially at maximum power point conditions.

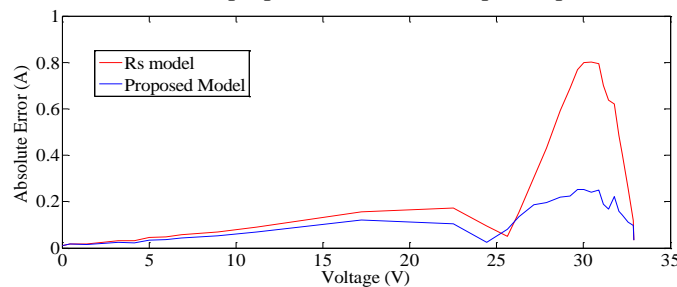


Fig. 6. Comparison of absolute error of KC200GT Module at STC

The proposed model is validated at $G=800\text{ W/m}^2$ and nominal operating cell temperature condition (NOCT) wherein the parameter values of these conditions are specified in the manufacturers datasheet. The nominal operating cell temperature is $(47\pm 2)^{\circ}\text{C}$. The parameters used for comparison are maximum power (P_m), Voltage at maximum power (V_m), open circuit voltage (V_{oc}) and short circuit current (I_{sc}). All these parameters are taken at NOCT. The results obtained from the datasheet are compared with model in [1] and the proposed model and relative errors are compared. The comparisons of different modules are shown from table 4.1 to table 4.4. It is evident from results that the proposed model is showing better results than model in [1].

For further validating the proposed model, a comparison is made with existing single diode and two diode models with the measured data published in [6]. The comparisons are made for SP-70 and ST-40 modules at different temperatures ($T=50^{\circ}\text{C}$, 25°C , 0°C , -25°C) and irradiance of $G=1000\text{ W/m}^2$. The parameters used for comparison are maximum power (P_{mp}) and voltage at maximum power (V_{mp}) at that particular environmental condition. All the models are compared by means of relative error. Relative Error (RE) is the ratio of difference between the measured value and simulated value to

measured value. In some cases the value from datasheet is considered as measured value. The comparisons of SP-70 and ST-40 modules are depicted in table 5.1 and table 5.2 respectively. The proposed model shows better results than the existing single diode model in all the cases. It shows better results than existing double diode model in some of the cases, but at low temperature conditions the double diode model gives better results or nearly similar results.

4.2 Validation of under Non-Uniform Irradiance Conditions

For validating the model in non-uniform irradiance conditions, the results obtained with the proposed model is compared with work carried out in [9]. The authors in [9] used a real time emulator presented in [17] for validation of model along with some other existing models. In [17], an Artificial Neural Network based real time PV emulator that is used to emulate PV characteristics under partial shading conditions is used for validating the proposed model under non-uniform irradiance conditions. In order to validate the behavior of the proposed system a 20×3 Series-Parallel (SP) Configuration is implemented using MATLAB. The 20×3 array is used is

divided into four sub-sections each of 5×3 such that each sub-section receives same irradiance. Ten different shading patterns are considered as shown in table 6. Each shading pattern is evaluated at two different temperatures i.e., 25°C and 50°C . The parameters used for comparison are global peak power (P_m) and voltage at global peak power (V_m) at that particular environmental condition.

Figs. 7 and 8 show the I - V and P - V characteristics for first two shading pattern of table 6 at 25°C . The number of steps in the I - V curve and number of peaks in the P - V Curve depends

on array configuration, irradiance and shading pattern [18]. Table 7.1 and 7.2 show the results of 20×3 array at 25°C and 50°C respectively. The relative error is computed with respect to model in [9] and [12] and the proposed model is compared with existing models. Relative errors of global peak power for all shading patterns for proposed model and existing models are depicted in fig. 8 (a) and 8(b) for 25°C and 50°C respectively. It can be observed that the proposed model is giving better result than existing models in most of the cases.

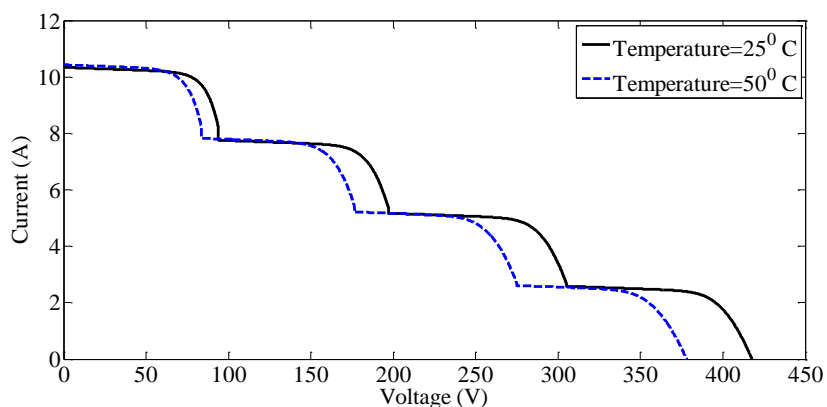


Fig. 7. I - V Curve of shading Pattern-1

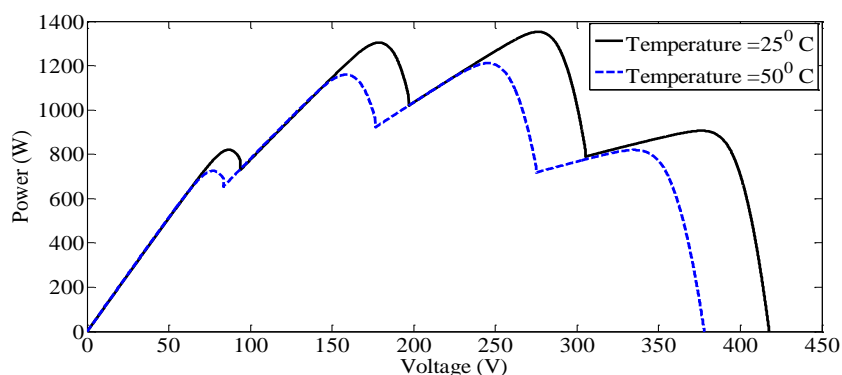


Fig. 8. P - V Curve of shading Pattern-1

Table 4.1. Comparison of Values at $G= 800 \text{ W/m}^2$ and NOCT for SP-70 module

Parameters	Values in Datasheet	Rs model [3]	1-D model [1]	Proposed model	RE (%) Rs model [3]	RE (%) 1-D model [1]	RE (%) Proposed model
P_{mp} (W)	51	51.83	51.23	51.14	1.627	0.451	0.274
V_{mp} (V)	15.1	14.751	15.15	15.13	2.311	0.331	0.198
V_{oc} (V)	19.6	19.7	19.6	19.6	0.51	0	0
I_{sc} (A)	3.8	3.792	3.792	3.792	0.21	0.21	0.21

Table 4.2. Comparison of Values at $G= 800 \text{ W/m}^2$ and NOCT for KC200GT module

Parameters	Values in Datasheet	Rs model [3]	1-D model [1]	Proposed model	RE (%) Rs model [3]	RE (%) 1-D model [1]	RE (%) Proposed model
P_{mp} (W)	142	144.5	142.124	142.005	1.76	0.087	0.0003
V_{mp} (V)	23.2	23.37	23.46	23.46	0.732	1.12	1.12
V_{oc} (V)	29.9	28.5	29.77	29.77	4.68	0.434	0.434
I_{sc} (A)	6.62	6.62	6.62	6.62	0	0	0

Table 4.3. Comparison of Values at G= 800 W/m² and NOCT for SW 235 module

Parameters	Values in Datasheet	Rs model [3]	1-D model [1]	Proposed model	RE (%) Rs model	RE (%) 1D model [1]	RE (%) Proposed model
P_{mp} (W)	170.4	171.56	170.569	170.45	0.683	0.1	0.0289
V_{mp} (V)	27.1	27.11	27.25	27.23	0.037	0.553	0.479
V_{oc} (V)	33.5	33.9	33.86	33.8	1.19	1.07	0.89
I_{sc} (A)	6.73	6.73	6.73	6.73	0	0	0

Table 4.4. Comparison of Values at G= 800 W/m² and NOCT for ST-40 module

Parameters	Values in Datasheet	Rs model [3]	1-D model [1]	Proposed model	RE (%) Rs model [3]	RE (%) 1D model [1]	RE (%) Proposed model
P_{mp} (W)	27.7	28.39	28.08	28.04	2.49	1.37	1.22
V_{mp} (V)	14.7	14.4	14.75	14.73	2.04	0.34	0.204
V_{oc} (V)	20.7	20.65	20.65	20.65	0.241	0.241	0.241
I_{sc} (A)	2.2	2.15	2.15	2.15	2.27	2.27	2.27

Table 5.1. Comparison of Values at different temperature conditions for SP-70 module

Temperature	Measured data	R_s model [3]	1-D model [6]	2-D model [6]	Proposed model	RE (%) 1D model [6]	RE (%) 2D model [6]	RE (%) Proposed model
50 ⁰ C	$P_{mp}=62.13W$ $V_{mp}=14.60V$	61.48 W 14.09V	61.75W 14.6 V	61.89 W 14.6 V	62.03 W 14.6 V	0.612 0	0.386 0	0.161 0
25 ⁰ C	$P_{mp}=70.12W$ $V_{mp}=16.50 V$	70.12 W 15.98 V	70.12 W 16.5 V	70.12 W 16.5 V	70.12 W 16.5 V	0 0	0 0	0 0
0 ⁰ C	$P_{mp}=77.88 W$ $V_{mp}=18.40 V$	78.78 W 17.89 V	78.19 W 18.5 V	77.91 W 18.5 V	78.12 W 18.45 V	0.39 0.543	0.04 0.543	0.308 0.271
-25 ⁰ C	$P_{mp}=85.75 W$ $V_{mp}=20.30 V$	87.41 W 19.85 V	86.32 W 20.5 V	85.7 W 20.35 V	85.99 W 20.46 V	0.664 0.985	0.058 0.246	0.279 0.788

Table 5.2. Comparison of Values at different temperature conditions for ST-40 module

Temperature	Measured data	R_s model [3]	1-D model [6]	2-D model [6]	Proposed model	RE (%) 1D model [6]	RE (%) 2D model [6]	RE (%) Proposed model
50 ⁰ C	$P_{mp} = 34 W$ $V_{mp}=14.1 V$	33.48 W 13.811V	33.69 W 14.3 V	33.71W 14.2272 V	33.77 W 14.24 V	0.911 1.42	0.852 0.921	0.676 0.992
25 ⁰ C	$P_{mp}=40 W$ $V_{mp}=16.6 V$	40 W 16.14 V	40 W 16.6 V	40 W 16.6 V	40 W 16.6 V	0 0	0 0	0 0
0 ⁰ C	$P_{mp}=46 W$ $V_{mp}=19.1 V$	46.67 W 18.55 V	46.42 W 19 V	46.33 W 19.10 V	46.32 W 19.07 V	0.913 0.523	0.717 0	0.695 0.157
-25 ⁰ C	$P_{mp}=52 W$ $V_{mp}=21.6 V$	53.45 W 21.02 V	52.92 W 21.6 V	52.69 W 21.6 V	52.66 W 21.6 V	1.769 0	1.326 0	1.269 0

Table 6. Shading patterns

	Shading Pattern			
	A	B	C	D
1	1	0.75	0.5	0.25
2	0.75	0.25	0.25	0.1
3	1	0.5	0.3	0.1
4	0.8	0.6	0.4	0.2
5	0.9	0.6	0.3	0.1
6	0.6	0.5	0.4	0.3
7	0.75	0.5	0.2	0.1
8	1	0.6	0.3	0.15
9	1	1	0.5	0.25
10	1	0.2	0.5	0.2

Table 7.1. V_m and P_m outputs of 20X3 array under partially shaded condition at 25°C

	Shading Pattern				P& O [9]		ANN [23]		2D model [9]		1D model [18]		Proposed Model	
	A	B	C	D	V_m (V)	P_m (W)	V_m (V)	P_m (W)	V_m (V)	P_m (W)	V_m (V)	P_m (W)	V_m (V)	P_m (W)
1	1	0.75	0.5	0.25	338.29	856.99	241.01	1213.4	244	1220.2	241	1152.5	244	1211.8
2	0.75	0.25	0.25	0.1	325	329.46	229.95	560.97	231	553.01	74.5	509.66	225.2	532.5
3	1	0.5	0.3	0.1	336.08	339.24	152.56	755.81	161	790.67	158.5	747	161	783.7
4	0.8	0.6	0.4	0.2	325.02	677.21	241.01	964.26	243	965.92	238	902.5	242.01	951.6
5	0.9	0.6	0.3	0.1	334.2	339.93	150.35	885.98	158	935.20	156	865.2	159	927.6
6	0.6	0.5	0.4	0.3	322.81	453.44	322.81	979.39	323	964.16	312	882.15	318.3	935.6
7	0.75	0.5	0.2	0.1	329.45	333.01	150.35	735.27	158	774.04	154.5	710.5	157.3	761.4
8	1	0.6	0.3	0.15	336.08	509.23	150.35	895.62	160	943.68	157.5	876.5	160.6	938.7
9	1	1	0.5	0.25	340.5	863.12	143.72	1351.1	152	1446.9	150.5	1381.5	154.5	1450.1
10	1	0.2	0.5	0.2	336.08	681.71	232.16	1136.5	235	1143.5	231	1069	235.2	1123.4

Table 7.2. V_m and P_m outputs of 20X3 array under partially shaded condition at 50°C

	Shading Pattern				P& O [9]		ANN [23]		2D model [9]		1D model [18]		Proposed Model	
	A	B	C	D	V_m (V)	P_m (W)	V_m (V)	P_m (W)	V_m (V)	P_m (W)	V_m (V)	P_m (W)	V_m (V)	P_m (W)
1	1	0.75	0.5	0.25	384.72	971.44	276.38	1383.1	275	1359.6	271.5	1287.1	275.5	1356.6
2	0.75	0.25	0.25	0.1	373.6	377.78	263.12	646.13	263	620.9	80	577.5	85	628.7
3	1	0.5	0.3	0.1	382.51	387.11	174.67	866.86	180	883.4	178.5	830	181	878
4	0.8	0.6	0.4	0.2	380.3	770.38	274.17	1100	272	1077.7	268.5	1004.3	273	1062
5	0.9	0.6	0.3	0.1	382.51	387.7	172.46	1020.6	178	1047.7	177.5	991	179.3	1042.7
6	0.6	0.5	0.4	0.3	179.25	1117.4	369.25	1117.4	360	1076.8	352.5	980	360.4	1047
7	0.75	0.5	0.2	0.1	375.88	381.06	172.46	847.77	177	867.6	174.5	813.5	177.7	857.05
8	1	0.6	0.3	0.15	382.51	580.18	174.67	1030.4	179	1055.2	177.6	1000.2	180.9	1052.9
9	1	1	0.5	0.25	386.93	977.16	165.83	1566.3	171	1632.4	169.5	1566	174	1640
10	1	0.2	0.5	0.2	382.51	774.62	267.54	1301.6	266	1282.4	231	1072.5	265.5	1265

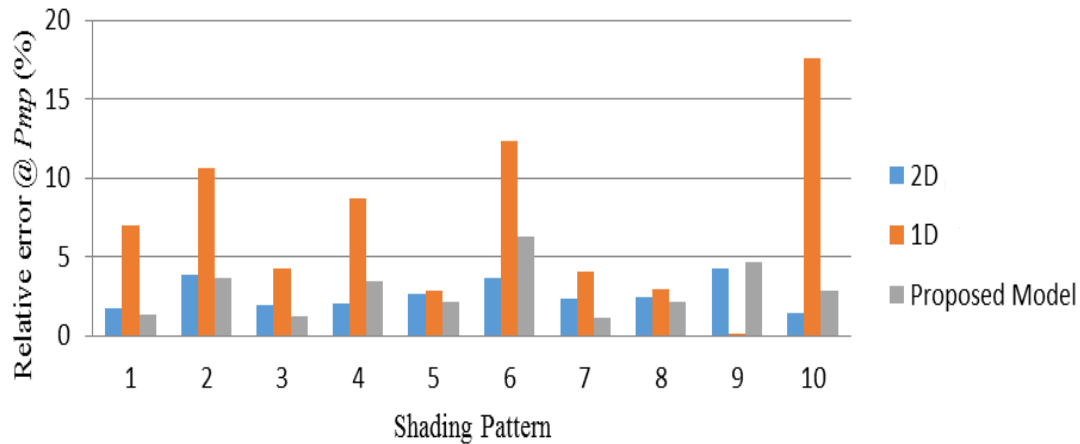


Fig. 8 (a) Relative Error of Ten Shading Patterns at 25°C

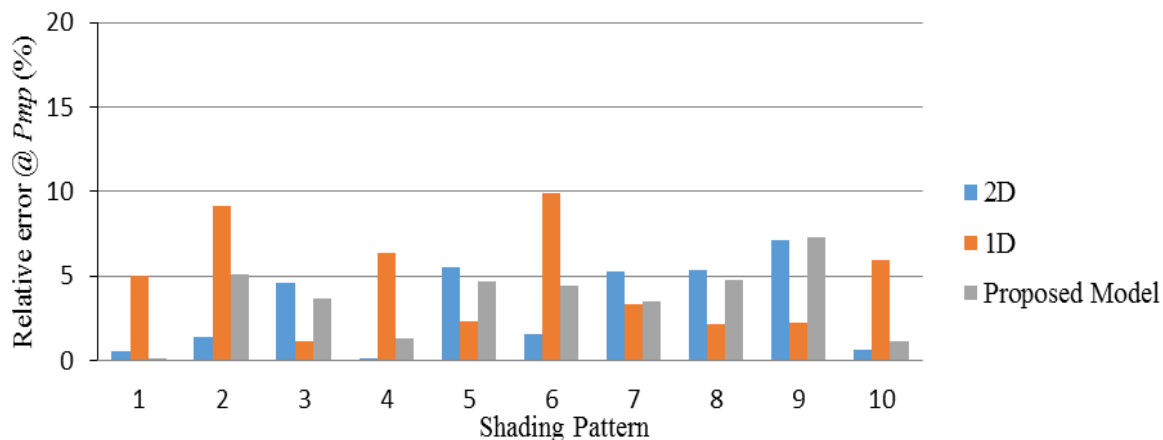


Fig. 8. (b) Relative Error of Ten Shading Patterns at 50°C

5. Conclusions

A method of modeling photovoltaic array in both uniform and non-uniform irradiance conditions is presented using a single diode model. A method of finding the equivalent circuit parameters by adaptively incrementing the series resistance is presented. This leads to decrease in computational time. The proposed model is validated with experimental results, datasheet values and other models in the literature. The model is giving better results than existing single diode model in all the cases and it is giving better result than two diode model in most of the cases. So the proposed model is a trade-off between complexity and accuracy. The model for uniform irradiance is extended for non-uniform irradiance. The results are validated with existing models and it is found that the model of non-uniform irradiance is giving better results in most of the cases.

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