Simple and Accurate Method of Modeling Photovoltaic Module: a Different Approach

Debashisha Jena
Electrical and Electronics Engineering
National Institute of Technology Karnataka
Surathkal, India

Vanjari Venkata Ramana
Electrical and Electronics Engineering
National Institute of Technology Karnataka
Surathkal, India

Abstract— **This paper proposes a different method of modeling Photovoltaic (PV) System in uniform irradiance conditions. It provides a simple and accurate method of modeling PV system using a single diode model by considering series and shunt resistance. This model computes five parameters and is having better accuracy than the existing models in literature. The accuracy of the proposed modeling technique is validated by comparing the model with the experimental values and datasheet values. The proposed model can be extended for modeling the effect of non-uniform irradiance conditions on PV system and also to track the maximum power from the PV source under non-uniform irradiance conditions.**

Index Terms— Photovoltaic system, equivalent circuit, single diode, uniform irradiance, modeling

I. Introduction

The sources of generating electricity are fossil energy (coal, oil and gas), hydro energy, nuclear energy, renewable energy (solar, wind, biomass etc.). The conventional energy sources like coal, nuclear, gas are available in limited quantities and they cannot be renewed at the rate of consumption. Since the energy sources like coal, hydro, nuclear are centralized at remote places they need to be transmitted over long distances after generation thereby the losses in transmission system increases. In order to overcome the limitations of conventional energy sources there is a need to look at alternative source of energy. The alternative sources of energy can be wind, solar, small hydro, biomass etc. Electricity using sun can be generated using Solar Photovoltaic and Solar thermal. The energy conversion of Solar Photovoltaic is a simpler process compared to solar thermal and wind. After hydro and wind, the third most important renewable source is solar photovoltaic in terms of global installed capacity [1].

Photovoltaic (PV) system directly converts sunlight into electricity. The fundamental device in a Photovoltaic system is the Photovoltaic cell. Mono-Crystalline Silicon, Multi-Crystalline Silicon, Amorphous Silicon, Cadmium Telluride, Copper Indium Gallium Sulphide, etc. are presently employed in manufacturing a photovoltaic cell [1]. A photovoltaic cell is a semiconductor diode whose p–n junction is exposed to light. The light incident on the photovoltaic cell generates charge carriers that produce electric current. The entire photovoltaic phenomena can be described as absorption of solar radiation, generation of charge carriers, transportation of charge carriers, and collection of these charges at the terminals of photovoltaic devices. A single cell can produce around 0.7 V. So the PV Cells are arranged in series to form modules. Modules are connected in series or parallel to form panels and group of panels constitute an array [6].

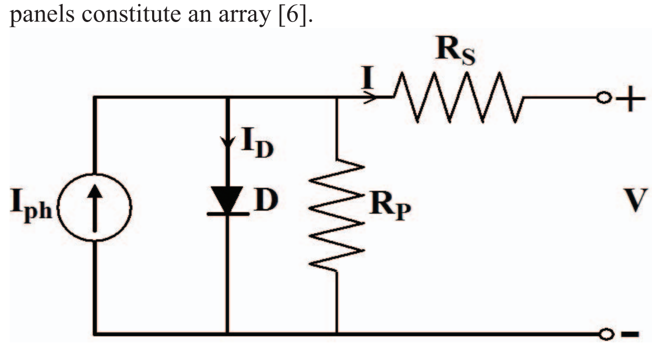

Fig 1. Single diode model

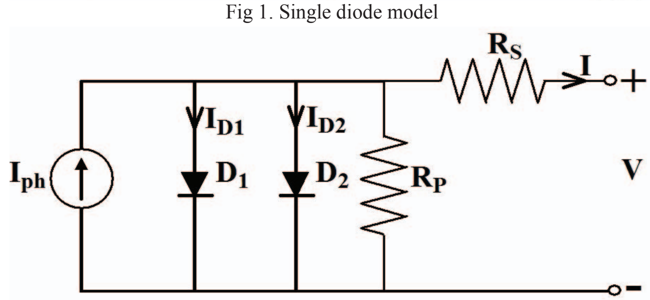

Fig 2. Two diode model

The PV model takes the temperature (T) and irradiance (G) as input and produces the electrical parameters of the equivalent circuit model as output. The equivalent circuit is depicted in Fig.1. The electrical parameters of equivalent circuit viz., Photovoltaic current or Light Generated Current (I_{ph}), Reverse Saturation Current of diode (I_o), Diode Ideality factor (A), Series Resistance (R_s) and Shunt Resistance (R_p) will be determined for modeling a Photovoltaic source. The current produced by PV source depends on amount of incident solar radiation falling on PV Surface. So a current source (I_{ph}) is represented in PV cell equivalent model. The recombination losses in the quasi-neutral region are represented by the diode connected anti-parallel to the current source. It is connected anti-parallel because the current due to recombination flows in opposite direction to the light generated current. The reverse saturation current (I_o) and diode ideality factor (A) are the parameters to be determined for finding diode current. The resistance of the metal contacts and the resistance to the flow of electrons in the semi conductor are represented by series resistance (R_s). The shunt resistance (R_p) represents the resistance offered to leakage path of the current flow in a PV cell and therefore, it is represented in parallel with the current source [1]. Fig. 1 is a single diode model. Fig. 2 represents a double diode model. In this model an extra diode is connected anti-parallel to current source which represents the recombination losses in the depletion region. Apart from other parameters in single diode model, the reverse saturation current (I_{o2}) and diode ideality factor (A_2) are the extra parameters that are to be calculated from two-diode model [7].

Since the parameters of the equivalent circuit are not available in the manufacturer's datasheet, they are computed from the data available in the datasheet. The values available in the datasheet are nominal open circuit voltage (V_{ocn}), nominal short circuit current (I_{scn}), current at maximum power point (I_{mp}), voltage at maximum power point (V_{mp}), temperature coefficients of voltage (K_V) and current (K_I), number of cells connected in series (N_s). The values of the datasheet are specified at Standard Test Condition (STC). The voltage temperature coefficient (K_V) and current temperature coefficient (K_I) that are specified in the manufacturer datasheet are used for considering the effect of temperature on open circuit voltage and short circuit current [6].

There are many models in the literature that represents a solar PV array. The models proposed in [2] and [3] are single diode models by neglecting shunt resistance. These models give less accurate results at different irradiance and temperature conditions. A two diode model is proposed in [4]. Even though this model is accurate, the parameters of the equivalent circuit are calculated with the values that are not available in the datasheet such as band gap energy (E_g). The authors in [5] computed the values of series resistances, shunt resistance and diode ideality factor in an iterative manner by solving non-linear equations using numerical techniques. This leads to huge computational burden. The authors in [6] proposed a method for finding the values of R_s and R_p as a pair by incrementing the values of R_s and finding the corresponding value of R_p by equating $P_{max,m} = P_{max,e}$. Where $P_{max,m}$ is the maximum power obtained from the mathematical model and $P_{max,e}$ is the maximum power given in datasheet. The iteration is continued until $P_{max,m} = P_{max,e}$. This 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}). In order to overcome the limitations of the existing models, a different model is proposed in this paper. The proposed model is a tradeoff between simplicity and accuracy.

The proposed model is presented in section II. The results obtained from the proposed model are compared with the existing models in section III. Conclusions are presented in section IV.

II. PROPOSED MODEL

A single diode model that is depicted in fig.1 is considered. By applying KCL to the fig. 1 the value of output current is obtained and is given by eq. (1).

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

The equations of the solar PV equivalent circuit are represented in two different operating conditions viz., open circuit conditions and short circuit conditions. 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).

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

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

A. 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 calculated ($P_{max,m}$) from the model. The value of R_p is given by eq. (4).

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

The initial value of Series Resistance is zero and Shunt Resistance is given as shown in equation (5) [6].

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

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 [6].

B. 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).

C. 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).

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

I_{phn} is the photovoltaic current at 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 [5].

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

$$V_{oc} = \left(V_{ocn} + K_V dT\right) \tag{8}$$

The effect of irradiance on open circuit voltage is obtained by substituting the values of I_{sc}, I_{ph} in equation (4) and then solving for open circuit voltage.

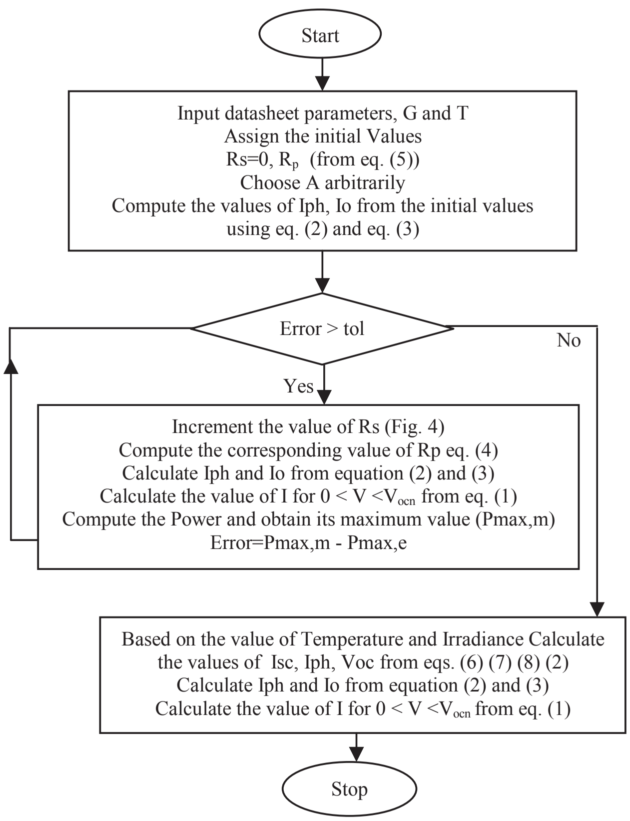

Fig. 3 Flow Chart of the Proposed Model

D. Special Case

A special case is considered in which all the numerical values are assumed. Let Maximum Power Specified in datasheet, $P_{max,e}$=235 W. Let for R_s = 0.251 Ω; if the value of $P_{max,m}$ =234.5 W; then absolute error =0.5 W. Let the tolerance limit, tol= 0.0001. For next increment if R_s=0.252 Ω and if $P_{max,m}$ =235.2W then absolute error=0.2 W. For the next increment value of R_s, the $P_{max,m}$ will further increase. So the method will diverge. This implies that value of series resistance lies between 0.251 Ω and 0.252 Ω. Similar problem arises while calculating the value of R_p. The value of R_p will go to negative in some cases leading to inaccurate results. This problem can be overcome by incrementing the value of R_s based on the algorithm given in fig. 4.

```
While (error > tol)
{
    if (error < limit)
    {
        Rs = Rs + (alpha*Rsinc);
    }
    else
    {
        Rs= Rs+ Rsinc;
    }
    // rest of program
}
```

Fig. 4 Incrementing Series Resistance

The tolerance (tol) is the difference between maximum power of the mathematical model and maximum power of datasheet. The value of tolerance (tol) ideally should be zero but for convenience it is taken as 10^{-4}. A pre-specified limit (limit), is chosen such that if the error is less than the limit, then the value of R_s to be incremented, R_{sinc} is multiplied by a value alpha. The value of limit and alpha are chosen arbitrarily such that better accuracy is obtained from the model. The value of alpha can be 0.1, 0.01 or any value that can be give better accuracy. The flowchart of the modeling procedure is presented in the figure 3.

III. RESULTS AND DISCUSSIONS

The modeling procedure presented is validated by using experimental results obtained from datasheet and the values extracted from manufacturer's datasheet. The proposed model is also compared with existing models in the literature. The summary of the specifications of manufacturers datasheet [8] are mentioned in Table 1. The calculated parameters of the single diode model that is proposed is presented in Table 2. Five parameters viz., I_{pv}, I_o, R_s, R_p, A are computed.

Table 1
Datasheet Parameters

	KC200GT [8]	SP70 [9]	ST40 [9]	SW 235 [10]
I_{scn} (A)	8.21	4.7	2.68	8.35
V_{ocn} (V)	32.9	21.4	23.3	37
I_{mp} (A)	7.61	4.25	2.41	7.85
V_{mp} (V)	26.3	16.5	16.6	30
K_v (V/ ^{0}C)	-0.123	-0.076	-0.1	-0.1258
K_I (mA/ ^{0}C)	3.18	2	0.35	2.839
N_s	54	36	36	60

Table 2
Parameters of Proposed Single Diode Model

	KC200GT	SP70	ST40	SW 235
I_{sc} (A)	8.21	4.7	2.68	8.35
V_{oc} (V)	32.9	21.4	23.3	37
I_{pv} (A)	8.213	4.7256	2.70	8.354
I_o (A)	1.5×10^{-7}	1.49×10^{-9}	2.9×10^{-10}	9.79×10^{-10}
Rs (Ω)	0.22	0.5	1.66	0.29
Rp (Ω)	649.5	93.25	192.5	570.1
A	1.3	1.1	1.1	1.05

I-V curves of KC200GT solar module under different shading conditions are plotted in Fig 5. The curves are plotted for proposed single diode model, R_s-model (single diode model with shunt resistance neglected) and experimental values extracted from datasheet. The proposed model and R_s-model exhibits similar results especially the prediction of maximum power at STC. This is because the algorithm proposed is based on the maximum power matching. However, when the shading level is decreasing, more accurate results are obtained for the proposed single diode model than the R_s-model. I-V curve of KC200GT at varying temperature conditions is presented in Fig. 6. As mentioned in previous paragraph, the R_s and 1-D model provide similar results at STC. But at temperature other than STC, the proposed single diode (1-D) model shows more accurate matching of I-V curves with the values extracted from datasheet than I-V curve of R_s-model.

The proposed model is compared with model present in [6] at NOCT (Nominal Operating temperature) and irradiance of 800W/m^2 which is generally given in some of the datasheets. The NOCT will be (47± 2)^{0}C. The comparisons are presented in Tables 3.1 to 3.4. The comparison of P_{mp}, V_{mp}, V_{oc}, I_{sc} at the above mentioned conditions of irradiance and temperature are presented. It can be seen that the proposed model exhibits better performance than the existing single diode model in [6]. Relative Error (RE) is the ratio of difference between the datasheet value and simulated value to datasheet value. It is used for comparison in table 3 and table 4.

In order to future validate the proposed model, a comparison is made between the existing single diode model (1-D), existing double diode model (2-D), proposed single diode model with the experimental values in [7]. The comparisons are made in table 4.1 and 4.2.The comparison is done for SP-70 and ST-40 datasheets at different temperatures. The experimental values of the maximum power and maximum voltage and the values of the parameters at maximum power conditions for existing 1-D and 2-D models are taken from [7]. It can be observed that the proposed single diode model is predicting more accurate result than 1-D model present in [7]. In most of the cases the proposed 1-D model is giving more accurate results than 2-D model in [7]. Although at some temperature conditions, 2-D model is giving better accuracy, the proposed model is giving more accurate results in most of the cases. So it can be chosen as a comfortable tradeoff between the existing 1-D model and 2-D model [7] i.e., the proposed model is trade-off between simplicity and accuracy.

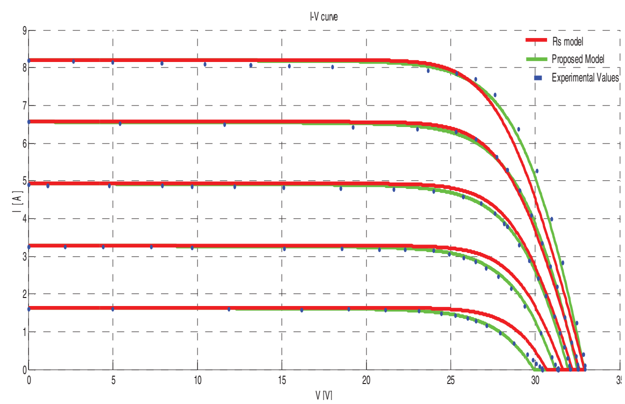

Fig 4. I-V Curve of KC200GT Module for different shading Conditions

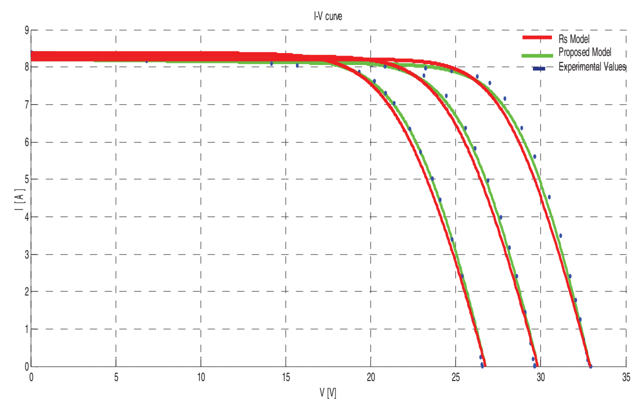

Fig. 5. I-V Curve of KC200GT Module for different Temperature Conditions

Table 3.1
Comparison of Values at G= 800 W/m^2 and NOCT for SP-70 module

Parameters	Values in Datasheet	Rs model	1-D Model [6]	Proposed model	RE (%) Rs model	RE (%) 1-D Model [6]	RE (%) Proposed model
Pmp (W)	51	51.83	51.23	51.14	1.627	0.451	**0.274**
Vmp (V)	15.1	14.751	15.15	15.13	2.311	0.331	**0.198**
Voc (V)	19.6	19.7	19.6	19.6	0.51	0	**0**
Isc (A)	3.8	3.792	3.792	3.792	0.21	0.21	**0.21**

Table 3.2
Comparison of Values at G= 800 W/m^2 and NOCT for KC200GT module

Parameters	Values in Datasheet	Rs model	1-D Model [6]	Proposed model	RE (%) Rs model	RE (%) 1-D Model [6]	RE (%) Proposed model
Pmp (W)	142	144.5	142.124	142.005	1.76	0.087	**0.0003**
Vmp (V)	23.2	23.37	23.46	23.46	0.732	1.12	**1.12**
Voc (V)	29.9	28.5	29.77	29.77	4.68	0.434	**0.434**
Isc (A)	6.62	6.62	6.62	6.62	0	0	**0**

Table 3.3
Comparison of Values at G= 800 W/m^2 and NOCT for SW 235 module

Parameters	Values in Datasheet	Rs model	1-D Model [6]	Proposed model	RE (%) Rs model	RE (%) 1D Model[6]	RE (%) Proposed model
Pmp (W)	170.4	171.565	170.569	170.45	0.683	0.1	**0.0289**
Vmp (V)	27.1	27.11	27.25	27.23	0.037	0.553	**0.479**
Voc (V)	33.5	33.9	33.86	33.8	1.19	1.07	**0.89**
Isc (A)	6.73	6.73	6.73	6.73	0	0	**0**

Table 3.4
Comparison of Values at G= 800 W/m^2 and NOCT for ST-40 module

Parameters	Values in Datasheet	Rs model	1-D Model [6]	Proposed model	RE (%) Rs model	RE (%) 1D Model [6]	RE (%) Proposed model
Pmp (W)	27.7	28.39	28.08	28.04	2.49	1.37	**1.22**
Vmp (V)	14.7	14.4	14.75	14.73	2.04	0.34	**0.204**
Voc (V)	20.7	20.65	20.65	20.65	0.241	0.241	**0.241**
Isc (A)	2.2	2.15	2.15	2.15	2.27	2.27	**2.27**

Table 4.1
Comparison of Values at different temperature conditions for SP-70 module

Temperature	Measured data	Rs model	1-D Model [7]	2-D Model [7]	Proposed model	RE (%) 1D model [7]	RE (%) 2D model [7]	RE (%) Proposed model
50^0 C	Pmp=62.13W Vmp=14.60V	61.48 W 14.09V	61.75W 14.6 V	61.89 W 14.6 V	62.03 W 14.6 V	1.59 0	1.37 0	**1.06** **0**
25^0 C	Pmp=70.12W Vmp=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	Pmp=77.88 W Vmp=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	Pmp=85.75 W Vmp=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 4.2
Comparison of Values at different temperature conditions for ST-40 module

Temperature	Measured data	Rs model	1-D Model [7]	2-D Model [7]	Proposed model	RE (%) 1D model [7]	RE (%) 2D model [7]	RE (%) Proposed model
50^0 C	Pmp = 34 W Vmp=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	**0.674** **0.992**
25^0 C	Pmp=40 W Vmp=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	Pmp=46 W Vmp=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	Pmp=52 W Vmp=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**

IV. CONCLUSIONS

A simple and accurate modeling method of photovoltaic system with single diode model is proposed. The proposed model has shown better results than the existing models at different irradiance and temperature. Because of the simplicity and accuracy of the model, it can be extended for modeling and simulating the effect of non-uniform irradiance on a PV system. And also the proposed model can be used to track the Maximum Power Point under non-uniform Irradiance Conditions.

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