Error trend analysis of One and Two diode model Photovoltaic Module

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Abstract : This paper presents the variation in error between modeling and experimental results with temperature and irradiation of a solar photovoltaic (PV) panel. The main objective of the present work is to find the trend in which the error varies with temperature and irradiation. The modeling results are obtained using single and two diode PV model. The series and shunt resistances are determined using Newton-Raphson method. These modeling results are compared with the experimental results obtained by performing experiment on the VIKRAM ELDORA 40 PV panel using Ecosense insight solar training & research kit. The relative error between modeling and experimental results are computed and an error analysis is made, first keeping temperature constant and varying the irradiation, second by keeping irradiation constant and varying the temperature. This error analysis is useful for understanding the charge carrier transport mechanism inside the PV module and also helps the power converter designers in selecting the accurate PV model according to operating range of temperature and irradiation of PV devices.

***Index Terms* - Photovoltaic, module, modeling, single diode, two diode**

I. INTRODUCTION

Photovoltaic (PV) power market is expanding rapidly due to the growing interest in renewable energy resources. Therefore, the PV designers need a reliable tool which can accurately predict the electrical power produced by the PV arrays/panels of various sizes. A photovoltaic system directly converts sunlight into electricity. The basic device of a PV system is the photovoltaic cell. Photovoltaic energy conversion in PV cell consists of two steps. First, absorption of packets of solar energy called photons. This absorption of solar energy generates electron-hole pair. Second, the electron and hole are then separated by the structure of the PV device resulting into the generation of electrical power.

Many models have been proposed by various researchers namely, Ideal Single Diode Model (ISDM), series resistance model or Rs-model, Single Diode Model (SDM) and Two Diode Model (TDM). The simplest model is the ideal single diode model which contains a current source in parallel to a diode [1], [2]. The current source produces photon generated current which is directly proportional to solar irradiance. This model requires only three parameters, namely photon generated current, reverse saturation current of diode and diode ideality factor. Previous researchers have utilized circuit topologies for modeling the characteristics of the photovoltaic module subjected to temperature and irradiation variation.

An improvement of ideal single diode model is done by the addition of one series resistance and it is popularly known as series resistance model or Rs-model [3]-[7]. This model considers the ohmic losses due to levels of contact. These losses are represented by a series resistance Rs in the equivalent circuit. It exhibits serious deficiencies for modeling of the PV systems subjected to temperature variations. Its accuracy decreases at high temperature applications because it does not account for the open-circuit voltage coefficient [5].

Further extension of the Rs-model is the single diode model, shown in Fig. 1, which includes a shunt resistance in parallel to a diode [8]-[14]. Although some improvement is achieved in terms of accuracy, this model demands significant computing efforts due to five unknown parameters. This model is used by manufactures for providing the data sheets of their solar cells.

This single diode model was based on the assumption that there is no recombination of charge carriers but in a real cell recombination process takes place on the surface as well as within the volume of semiconductor material. Considering recombination process renders a more precise model known as two diode model [15]-[22]. The equivalent circuit of this model, shown in Fig. 2, takes into account the mechanism of electric transport of charges inside the cell. This model considers the recombination of charge carriers. In order to consider the recombination current component, the addition of an extra diode to single diode model increases the parameters to seven and the determination of these parameters is difficult due to implicit form of equation having two exponential terms which makes it less attractive than SDM despite of its higher accuracy. In the proposed work, single and two diode PV models are used for obtaining the modeling results.

II. DETERMINATION OF MODEL PARAMETERS

A. Determination of one diode model parameters

Fig. 1 shows one/single diode PV model where Rs and Rsh represents series and shunt resistances respectively, Iph is the light/photon generated current. The output current equation for this model is given as:

$$I = I_{ph} - I_o\left[exp\left(\frac{V+IR_s}{aV_T}\right)-1\right]-\frac{V+IR_s}{R_{sh}} \qquad (1)$$

In Eq. (1), Io is the saturation current, a is the diode ideality constant and the thermal voltage, V_T = NskT/q. Ns is the number of cells connected in series, k is the Boltzmann constant (1.3806503×10^{-23} J/K), q is electron charge (1.60217646×10^{-19} C) and T is temperature in kelvin. The series resistance is the sum of structural resistances of the PV device and Rsh represents the leakage current of the p-n junction and depends on the fabrication method of the photovoltaic cell.

The photon generated current of the PV cell is given by the following equation [11]

$$I_{ph} = \frac{G}{G_n}\left[I_{phn} + K_I(T-T_n)\right] \qquad (2)$$

From Eq. (2), it is clear that photon generated current depends on the solar irradiation, G (W/m^2) and temperature, T (in kelvin) of the device. In Eq. (2) Iphn is the photon generated current at nominal condition (25 ºC, 1000 W/m^2), K_I is the short-circuit current/temperature coefficient, Tn and Gn are the nominal temperature and nominal irradiation respectively.

The temperature dependence of diode saturation current, Io can be expressed as [11], [15]

$$I_o = \frac{I_{scn} + K_I(T-T_n)}{exp\left[\left(V_{ocn} + K_V(T-T_n)\right)/aV_T\right]-1} \qquad (3)$$

Where Iscn and Vocn are the nominal short-circuit current and nominal open-circuit voltage respectively, Kv is the open-circuit voltage/temperature coefficient. In practical PV devices the series resistance is very small and parallel resistance is large. Therefore, the assumption Isc≈Iph is generally used in modeling of PV devices.

III. DETERMINATION OF R_S AND R_{SH} USING SDM AND TDM

At maximum power point the maximum one diode modeling power (Pm1) is equal to the maximum experimental power (Pmaxe) i.e. Pmaxe=Pm1. Using Eq. (1) and solving for Rsh we have

$$R_{sh} = \frac{V_{mpp}\left(V_{mpp}+I_{mpp}R_s\right)}{V_{mpp}I_{ph} - V_{mpp}I_o exp\left[\frac{(V_{mpp}+I_{mpp}R_s)}{aN_s}\frac{q}{kT}\right] + V_{mpp}I_o - P_{max\,e}} \qquad (4)$$

Initial conditions for applying the Newton-Raphson method, shown in Fig. 3, to above equation are given as

$$R_s = 0\,, R_{sho} = \frac{V_{mpp}}{I_{scn}-I_{mpp}} - \frac{V_{ocn}-V_{mpp}}{I_{mpp}} \qquad (5)$$

The value of the diode ideality factor, initially, may be chosen arbitrarily (2>a>1) which can be modified in order to get the Newton-Raphson solution of Eq. (4).

In order to consider the recombination of charge carriers in space region, the addition of a diode to one diode model circuit results into two diode model as shown in Fig. 2.

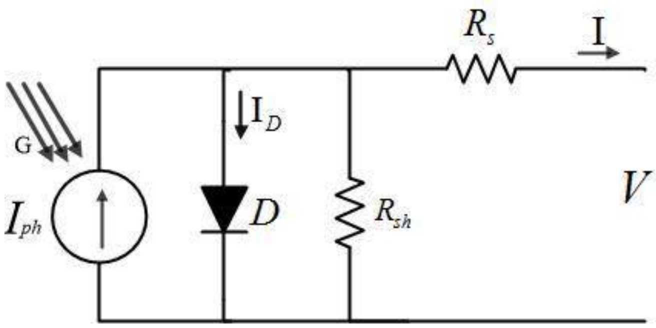

Fig. 1 One diode model for a PV module

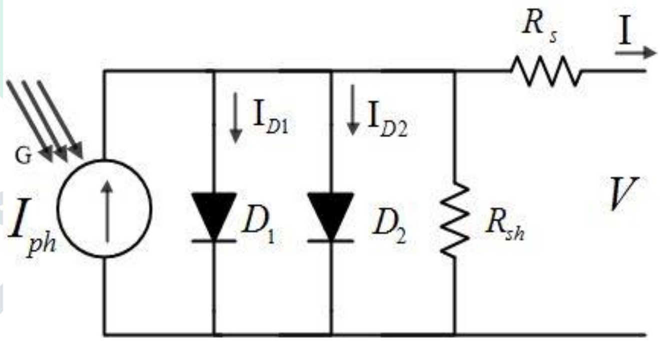

Fig. 2 Two diode model for a PV module

The following equation describes the output current of the PV module using two diode model

$$I = I_{ph} - I_{o1}\left[exp\left(\frac{V+IR_s}{a_1V_{T1}}\right)-1\right] - I_{o2}\left[exp\left(\frac{V+IR_s}{a_2V_{T2}}\right)-1\right] - \frac{V+IR_s}{R_{sh}} \qquad (6)$$

In Eq. (6), Io1, a1, VT1 and Io2, a2, VT2 are the reverse saturation current, diode ideality factor and thermal voltages for diode D_1 and D_2 respectively. By considering the equal magnitude of the saturation currents, Eq. (3) can be modified as [15]

$$I_{o1} = I_{o2} = I_o = \frac{I_{scn} + K_I(T-T_n)}{exp\left[\left(V_{ocn} + K_V(T-T_n)\right)/\{(a_1+a_2)/p\}V_T\right]-1} \qquad (7)$$

Where p is a variable that can be chosen so that (a1+a2)/p=1. Equation (6) can be written in terms of p as

$$I = I_{ph} - I_o\left[exp\left(\frac{V+IR_s}{V_T}\right) + exp\left(\frac{V+IR_s}{(p-1)V_T}\right)+2\right] - \frac{V+IR_s}{R_{sh}} \qquad (8)$$

The remaining unknown parameters (Rs, Rsh, a_1, a_2) of two diode PV model can be obtained by equating its maximum power output and maximum experimental output power i.e. Pmaxe=Pm2. Using Eq. (8) and solving for Rsh, we get

$$R_{sh} = \frac{V_{mpp}\left(V_{mpp}+I_{mpp}R_s\right)}{\left\{\begin{array}{c} V_{mpp}I_{ph} - V_{mpp}I_o exp\left[\frac{(V_{mpp}+I_{mpp}R_s)}{V_T}\right] \\ -V_{mpp}I_o\left[exp\left(\left(V_{mpp}+I_{mpp}R_s\right)/(p-1)V_T\right)+2\right] - P_{max\,e}\end{array}\right\}} \qquad (9)$$

Table 4.1: Calculated values of parameters at STC

One diode model parameters	***Calculated values***	***Two diode model parameters***	***Calculated values***
Iph	2.45 A	Iph	2.45 A
Io	2.99×10^{-8} A	$I_{o1}=I_{o2}=$ Io	1.26×10^{-10} A
a	1.3	$a_1=a_2$	1.2
Rs	0.010 ohm	Rs	0.01 ohm
Rsh	189.05 ohm	Rsh	132.68 ohm

Table 4.2: Specifications of ELDORA 40 PV module at STC

Voc	21.9 V	Pmaxe	40 W
Isc	2.45 A	K_V	-0.1230 V/K
Vmpp	17.4 V	K_I	0.0032 A/K
Impp	2.3 A	Ns	36

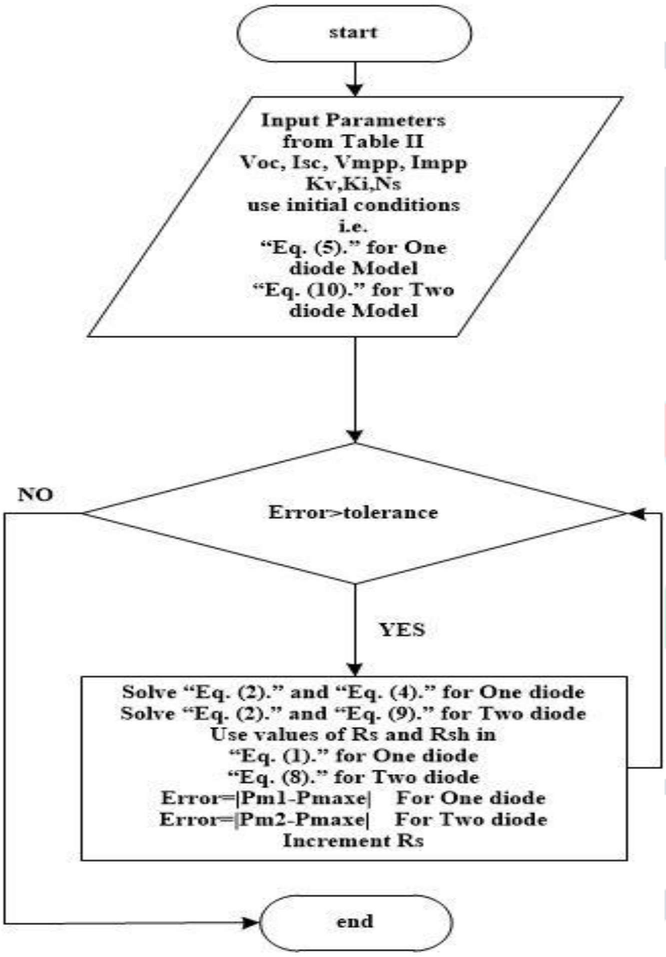

Fig. 3 Flowchart used for determination of Rs and Rsh

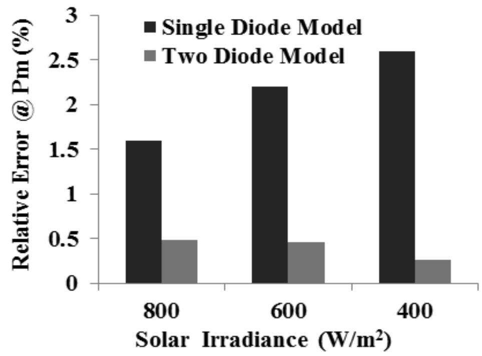

Fig. 4 Relative error at constant temperature (25°C)

Equation (9) can be solved in similar way that is used for one diode model with the following initial conditions

$$R_s = 0\,, R_{sho} = \frac{V_{mpp}}{I_{scn} - V_{mpp}} - \frac{V_{ocn} - V_{mpp}}{I_{mpp}} \qquad (10)$$

IV. Results and Discussion

Table 4.1 shows the calculated values of parameters at STC. The specifications of the ELDORA 40 PV module are summarized in Table 4.2. The maximum output power using one and two diode model at constant temperature and different irradiance are determined and compared with experimentally obtained power. The relative error for power output of one and two diode model at constant temperature are shown in Table 4.3 and calculated using following relation

%Error=[(Psim-Pexp)/Pexp]*100

In above relation Psim and Pexp are the simulated and experimental power respectively. Similarly the relative error for power output using one and two diode model at constant solar irradiance are calculated and shown in Table 4.4. The error trend for constant temperature and constant solar irradiance are shown in Fig. 4 and Fig. 5 respectively.

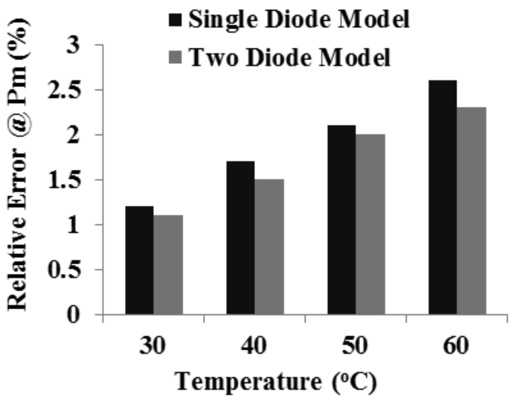

Fig. 5 Relative error at constant solar irradiance (1000 W/m^2)

Fig. 6 Ecosense Insight Solar PV training & research kit and Tenmars Solar power meter

Fig. 4 shows that at STC irradiance (1000 W/m^2) there is a small d and hence both the model provide results with comparable error. For lower irradiance two diode model provide more accurate results than one diode model. Fig. 5 shows the performance of one diode and two diode models when subjected to variation in module temperature. The irradiance is maintained constant (1000 W/m^2). From Fig. 5 it is clear that the more accurate results are obtained using two diode model for the given range of temperature (30°C-60°C) than single diode model. From Fig. 4 and Fig. 5, it is clear that both the model have approximately equivalent performance at temperature and irradiance near the STC values of temperature and irradiance.

Table 4.3 Relative errors for maximum power at constant temperature (25°C)

Solar Irradiance (W/m^2)	*One diode model power Pm1 (W)*	*Two diode model power Pm2 (W)*	*Experimental power Pexp (W)*	*Error (%) for one diode model*	*Error (%) for two diode model*
800	31.82	32.53	32.37	1.6	0.49
600	23.02	23.44	23.55	2.2	0.46
400	14.43	14.76	14.82	2.6	0.26

Table 4.4 Relative errors for maximum power at constant solar irradiance (1000 W/m^2)

Module Temperature (°C)	*One diode model power Pm1 (W)*	*Two diode model power Pm2 (W)*	*Experimental power Pexp (W)*	*Error (%) for one diode model*	*Error (%) for two diode model*
30	39.62	39.58	39.15	1.2	1.1
40	37.26	37.18	36.63	1.7	1.5
50	34.83	34.17	34.11	2.1	2.0
60	32.34	32.26	31.52	2.6	2.3

V. ACKNOWLEDGMENT

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