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Characterization Of Photovoltaic Panel Using Single Diode And Double Diode Models A Comparative Study With Experimental Validation

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***Abstract*— Photovoltaic (PV) cell directly converts sunlight into electricity, the device characteristics strongly depending in weather conditions. The PV cell represents a non-linear relationship between the current and voltage outputs. Several models for the PV cell have been proposed and developed in literature, some of them are simple to implement and others are complex. In this paper a comparative characterization of PV panel, using single diode and double diode models have been made with experimental validated using solar analyzer data. Statistical indicators, namely Root Mean Square Error (RMSE) and Mean Bias Error (MBE %) are used. The results shows that; double diode model has a better estimation results with best RMSE and MBE% values 0.197 and 0.125% respectively, best results for single diode model where RMSE=0.405 and MBE%=0.150%. However the computation time needed in double diode model was estimated 1.058 times that needed in single diode model. For fast estimation results, single diode model is recommended and for more accurate results double diode model is recommended.**

***Keywords*— PV Panel characterization, Single Diode Model, Double diode Model, Experimental I-V curve, Mathematical Modelling.**

I. Introduction

Kyoto-protocol followed by Paris climate change conference in December 12, 2015 [1, 2] made the majority of the world countries convinced by the necessity of reducing the emission of Carbone dioxide and greenhouse gases. That is by changing the dependence on fossil energy. Renewable sources are the best proposal for several researchers and scientists especially solar photovoltaic (PV) energybecause it has severaladvantages (e.g. clean and available almost at every point in the world).

Usually, PV panels are used as a sub-system in a complex electrical system. In order to design, optimize and/ or improve the quality of control modeling and simulation became an important step. Therefore the used PV panel model needs to be robust and well representing the behavior of the panel.

In modeling of the PV systems, Incident irradiation and cell temperature have a large effect in output performance of the PV panels. Several models are developed to represent the output characteristics of the PV panel (e.g. Single diode model (SDM), double diode model (DDM), three diode model[3],modified 3 diode model[4] and model based artificial neural network[5]). Nonetheless, single and double diode models are popular and most commonly used in literature due to their simplicity, less computational time and less parameters to identify [6,7]. Hence, the focus in this paper was in the tow last models (SDM and DDM).

Dehghanzadeh et al [8] proposed a new explicit model of double diode model for improving the accuracy and he recommended that the use of the model would be a better to do extensive simulation study in power electronics integrated by PV panels. Ritesh Dash and S.M Ali [9] made a mathematical modeling with a comparison of single and double diode models but without any validation. Mohammed Amine Fares et al [10] tested the characterization of PV panel using single diode model with experimental validation, but no comparison is done with double diode model. Furthermore, Vivek Tamrakar et al [7] studied characteristics of SDM and DDM but the verification was only by comparing curves with polycrystalline manufacturer datasheet. However few papers made a comparison between SDM and DDM outputcharacteristics with experimental validation data at various climate conditions (Irradiance and Ambient temperature). Therefore, the aim of this paper is to make a comparison of the characterization of PV panel using SDM

and DDM with experimental validation in order to choose the appropriate electrical equivalent model for the appropriate application.

II. Single diode equivalent model

In single diode model the PV cell is represented by a photo-electric current source I_{ph} in parallel with a *P–N* junction diode according to Shockley equation of semiconductor *P-N* junction under illumination [11]. Losses in the PV cell are modelled by tow resistances, Parallel resistance $R_p$corresponds to the leakage current in the *P–N* junction and series resistance *Rs* the losses due to the contact resistance between the silicon and electrodes surfaces Fig. 1 shows the equivalent model.

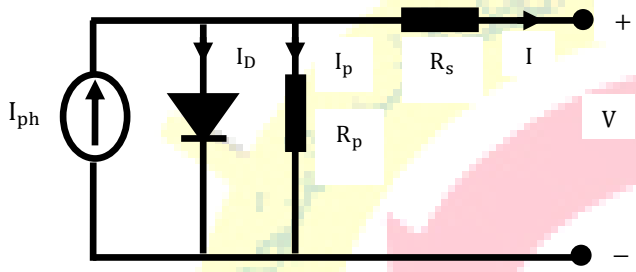

Fig. 1 Single diode model of the PV cell.

I and *V* are the output current and voltage of the cell respectively. Applying Kirchhoff's current law we can get the output current of the cell:

$$I = I_{ph} - I_D - I_p \quad (1)$$

$$I_D = I_s \times \left(\exp^{\left(\frac{V+I\times R_s}{n\times Vt}\right)} - 1\right) \quad (2)$$

Where *Is* is the saturation reverse current of the diode, *Rs* is the series resistance, *n* the ideality factor of the diode $V_t = Ns \times K \times T/q$ thermal voltage, *Ns* number of cells connected in series, q is the electron charge (1.60217646 1019 C), k is the Boltzmann constant (1.3806503 1023 J/K) and *T* is the temperature of the *P–N* junction in Kelvin.

$$I_p = \frac{V+I\times R_s}{R_p} \quad (3)$$

$$I = I_{ph} - I_s \times \left(\exp^{\left(\frac{V+I\times R_s}{n\times Vt}\right)} - 1\right) - \left(\frac{V+I\times R_s}{R_p}\right) \quad (4)$$

III. Identification of single diode model parameters

In single diode model, five parameters are unknown (I_{ph}, *Is*, *Rs*, R_p and *n*) and needs to be identified. There are several algorithms proposed for finding of single diode parameters. In our study we have applied Villalva algorithm [12] in order to identify the model parameters, because this algorithm is effective and less computation time.

A. *Identify the photo-current*I_{ph}

At short circuit conditions equation (4) can be expressed:

$$I_{sc} = I_{ph} - I_s \times \left(\exp^{\left(\frac{0+Isc\times R_s}{n\times Vt}\right)} - 1\right) - \left(\frac{0+Isc\times R_s}{R_p}\right) \quad (5)$$

Diode current I_D and leakage currant due to R_p are very small with respect to I_{ph}. The short circuit current I_{sc} is directly proportional to the incident irradiance thus, considering the effect of irradiance and cell temperature, I_{ph} is given [13]:

$$I_{ph} = [I_{sc} + Ki \times \Delta T]\frac{G}{G_{stc}} \quad (6)$$

Where *G* and *T* represent irradiance and temperature respectively, *Isc* is short circuit current at standard testcondition (*STC*: G=1000 W/m^2, T=25°C and AM=1.5), $G_{stc}$is standard irradiance (1000 W/m^2), K_i is the temperature coefficient on short circuit current *AM* is the air mass.

B. *Identify the diode reverse saturation current Is*

At open circuit conditions the equation (4) can be expressed:

$$0 = I_{ph} - I_s \times \left(\exp^{\left(\frac{V_{oc}}{n\times Vt}\right)} - 1\right) - \frac{V_{oc}}{R_p} \quad (7)$$

rearranging the equation we get expression for *Is*.

$$I_s = \frac{I_{sc}+Ki\times\Delta T-\frac{V_{oc}}{Rp}}{\exp^{\left(\frac{V_{oc}}{n\times Vt}\right)}-1} \quad (8)$$

$R_p \gg$ VcoThen, equation (7) can be written at standard conditions:

$$I_{s,stc} = \frac{I_{sc}+Ki\times\Delta T}{\exp^{\left(\frac{V_{oc}}{n\times Vt}\right)}-1} \quad (9)$$

A general formula for *Is* is given at any value of temperature [14]:

$$I_s = I_{s,stc} \times \left(\frac{T}{T_{stc}}\right)^3 \times \exp^{\left[\left(\frac{E_g\times q}{n\times K}\right)\times\left(\frac{1}{T_{stc}}-\frac{1}{T}\right)\right]} \quad (10)$$

*Eg*band gap energy of the *P-N* junction, *Tstc* the standard temperature (298.15 K), *T* is the cell temperature (K).

C. *Identify Rs and Rp*

At maximum power point equation (4) can be expressed:

$$P_m = V_m \times \left\{ I_{ph} - I_s \times \left(\exp^{\left(\frac{V_m + I_m \times R_s}{n \times Vt}\right)} - 1 \right) - \left(\frac{V_m + I_m \times R_s}{R_p} \right) \right\} (11)$$

rearranging the equation we get expression for *Rp*.

$$R_p = \frac{V_m + I_m \times R_s}{\left\{ I_{ph} - I_s \times \left(\exp^{\left(\frac{V_m + I_m \times R_s}{n * Vt}\right)} + -1 \right) - \frac{P_{m,e}}{V_m} \right\}} (12)$$

P_m is replaced by $P_{m,e}$ the maximum power value given in datasheet. Three parameters remains unknown (*n* ,*Rs* and *Rp*). The ideality factor *n* is given based on the technology of the PV modules, that is popularly utilized in literature based on different PV technologies given in Table 1 or close to that value [12].

TABLE IIDEALITY FACTOR VALUE BASED ON CELL TECHNOLOGY [12].

Cell technology	Ideality factor
Si-mono	1.2
Si-poly	1.3
a-Si-H	1.8
a-Si-H tandem	3.3
a-Si-H triple	5.0
CdTe	1.5
CIS	1.5
AsGa	1.3

Applying Villalva algorithm [15], equation (12) can be solved iteratively, by increasing the value of *Rs* while simultaneously calculating the *Rp* value, only one pair of *Rs* and *Rp* match the calculated value of maximum power point Pm,c with the value give in datasheet *Pm,e* following the flowchart in Fig. 2.
Iph approximated$I_{ph} \approx I_{sc}$ and the starting value of *Rs*, *Rs,0*=0.

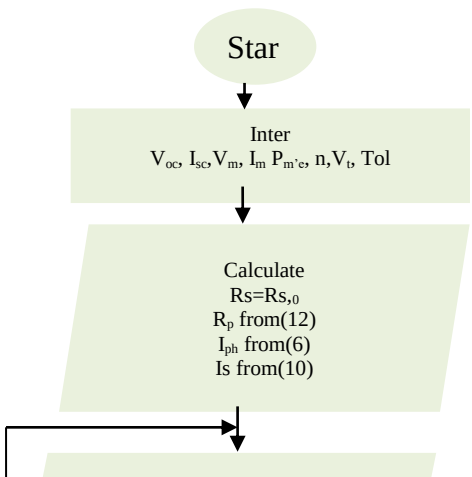

Fig. 2 Flowchart for Rs and Rp identification.

IV. DOUBLE DIODE EQUIVALENT MODEL

In double diode model additional junction current is introduced to compensate for the recombination loss in the depletion region [16]. The model is described in Fig. 3.

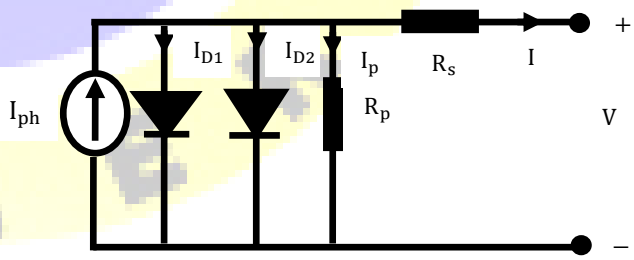

Fig. 3 Double diode model of the PV cell.

Applying Kirchhoff's current law we can get the output current of the cell:

$$I = I_{ph} - I_{s,1} \times \left(\exp^{\left(\frac{V+I\times R_s}{a1\times Vt}\right)} - 1\right) - I_{s,2} \times \left(\exp^{\left(\frac{V+I\times R_s}{a2\times Vt}\right)} - 1\right) - \left(\frac{V+I\times R_s}{R_p}\right) \quad (13)$$

Where I_{ph} the current generated by the incidence of light, I_{s1} and I_{s2} are the reverse saturation currents of diodes *1* and *2*, respectively. Vt_1 and Vt_2 ($Vt_{1,2}$= Ns×k×T/q) is the thermal voltage of the PV panel, *Ns* number of cells connected in series, *q* is the electron charge (1.60217646 1019 C),*k* is the Boltzmann constant (1.3806503 1023 J/K), and T is the temperature of the *P–N* junction in Kelvin. a_1 and a_2 represent the diode ideality factors.

V. Identification of Double Diode Model Parameters

A. Identify the photo-current I_{ph}

Photo-current equation in this model is the same used in single diode model:

$$I_{ph} = [I_{sc} + Ki \times \Delta T]\frac{G}{G_{stc}} \quad (14)$$

B. Identify the diode reverse saturation current $I_{s,1}$ and $I_{s,2}$

To simplify the study several papers made the assumed that, $Is_1=Is_2$ because no iteration is needed [16]. Both saturation currents can be calculated using the following analytical equation:

$$I_s = \frac{I_{sc}+Ki\times\Delta T}{\exp^{\left(\frac{V_{oc}}{\left(\frac{a1+a2}{p}\right)\times Vt}\right)}-1} \quad (15)$$

In accordance to Shockley's diffusion theory, a_1 must be unity [17]. However, the value of a_2 is flexible. Based on extensive simulation carried out, it is found that the best match between the proposed model and practical *I–V* curve is observed. Since $\frac{(a1+a2)}{P} = 1$ and $a_1 = 1 \rightarrow a2>1.2$ [16], In this study $a_2 = 2$, this assumption is widely used but not always true [16].

C. Identify R_s and R_p

At maximum power point equation (13) can be expressed, for a_1=1:

$$R_p = \frac{V_m+I_m\times R_s}{\left\{\left[I_{ph}-I_s\times\left(\exp^{\left(\frac{V_m+I_m\times R_s}{Vt}\right)}+\exp^{\left(\frac{V_m+I_m\times R_s}{(P-1)\times Vt}\right)}-2\right)\right]-\frac{P_{m,e}}{V_m}\right\}} \quad (16)$$

All parameters but *Rs* and R_p are known, equation(16) can be solved using the same algorithm in single diode model by iteratively increasing the value of *Rs* while simultaneously calculating the R_p value, only one pair of *Rs* and R_p match the calculated value of maximum power point $P_{m,c}$with the value give in datasheet $P_{m,e}$. This algorithm is effective because it makes sure that the estimated $P_{m,c}$ is very near to the experimental value $P_{m,e}$.

I_{ph} approximated $I_{ph} \approx I_{sc}$ and the starting value of *Rs*, $R_{s,0}$=0.

VI. Materials and Methods

To obtain the simulated *I-V* curve, a MATLAB code was created to solve output current in both equations (4) and (13) numerically using Newton-Raphson method, where a general formula for the method is given:

$$f(In+1) = In - \frac{f(In)}{f'(In)} \quad (18)$$

for single diode model.

$$F = 0 = I_{PH} - I - I_s \times \left(EXP^{\left(\frac{V+I\times R_S}{N\times VT}\right)} - 1\right) - \frac{V+I\times R_S}{R_P} \quad (19)$$

for double diode model.

$$f = 0 = I_{ph} - I - I_{s,1} \times \left(\exp^{\left(\frac{V+I\times R_s}{a1\times Vt}\right)} - 1\right) - I_{s,2} \times \left(\exp^{\left(\frac{V+I\times R_s}{a2\times Vt}\right)} - 1\right) - \frac{V+I\times R_s}{R_p} \quad (20)$$

In addition, to validate the results a silicon polycrystalline 175Wp (by *SolarWorld* [Online,2018]www.solarworld.com)PV panel is used. Cell temperature was measured using a temperature sensor (PT1000, range of measurement (-20°C to +100°C ±0.8°C), the solar irradiance measured using a Pyranometer *type 3.3* (Measuring rang 0~1300W/m2, Temperature response – 20°C +60°C, Absolute error <10% and Voltage-currentOperation9~30V DC, 4~20mA). The physical parameters of the PV panel after identification are in Table 3. The Experimental*I-V*curves were extracted using*VA200 Solar Module Analyzer*[Online,2018]<https://langlois-france.com>, technical instruments details given in table (4).

TABLE II.PV module parameters at STC[18].

Parameter	Value
Pm,e	175Wp
Voc	44.2V
Vm	36.0V
Isc	5.30A
Im	4.87A
Ns	72
Np	1
NOCT	47°C

Ki	0.034%/K
Kv	-0.34%/K
Kp	-0.48%/K

TABLE IIIMODEL PARAMETERS AFTER IDENTIFICATION.

parameter	Ideality factor n [1]	Series Resistance Rs[Ω]	Parallel Resistance Rp[Ω]
Single diode Model	1.3	0.26	270.43
Double diode Model	a_1=1 a_2=2	0.52	212.38

TABLE IV Solar MODULE ANALYZER SPECIFICATIONS [19].

Solar Module Analyzer	Ref VA200
DC Voltage Measurement	0-60V
DC Current Measurement	0-6A
AC Adapter	AC 110V or 220V input, DC 12V / 1-3A output
Dimension	257(L) x 155(W) x 57(H) mm
Weight	1160 gms Battery Included (approx.)
Environment limits	0°C ~ 50°C, 85% RH
Storage limits (Batteries)	-20°C ~ 60°C, 75% RH
Best Resolution	1mV±1%, 0.1mA ±1%
Sampling Time of Data logging	0 ~ 9999 mS

VII. STATISTICAL INDICATORS

Statistical indicators Root Mean Square Error (RMSE) and Mean Bias Error (MBE%) are used for testing the accuracy of the PV models.

$$\text{RMSE}=\left[\sum(\text{Im}-\text{Ie})^2/\text{N}\right]^{1/2} \quad (21)$$

$$\text{MBE }\%=\text{N}^{-1}\times\frac{\sum(\text{Im}-\text{Ie})}{\sum\text{Im}}\times 100 \quad (22)$$

Where *Ie* and I_m the Nth estimated and measured values respectively, *N* total number of samples. This test provides information on the long term performance, a closest value to zero of RMSE and MBE% is desired and ideally a zero value should be obtained.

VIII. RESULTS AND DISCUSSION

In this study, four (4) testes have been made for the PV panel at various climate conditions (G=1080 W/m²& T=50°C, G=735 W/m²& T=44°C, G=531 W/m²& T=41°C and G=362 W/m²& T=39°C), G is the incident irradiance and T is the cell temperature.

Fig .4 and Fig. 5 represents the *I-V* characteristics at G=735W/m² T=44°C and G=531W/m² T=41°C respectively. In both curves we can see that, as long as voltage increases the current decreases until the current reaches the zero value due to increasing in load resistance. At the first zone (zone1, V=[0v 25v]) a large changing in voltage value leads to small changing in output current, PV panel in this zone behaves like a current source where the effect of R_p is high at that zone. At the second zone (zone2, V=[35v38v]), a small changing in voltage value leads to large changing in output current, PV panel in at that zone behaves like a voltage source where the effect of is *Rs* high.

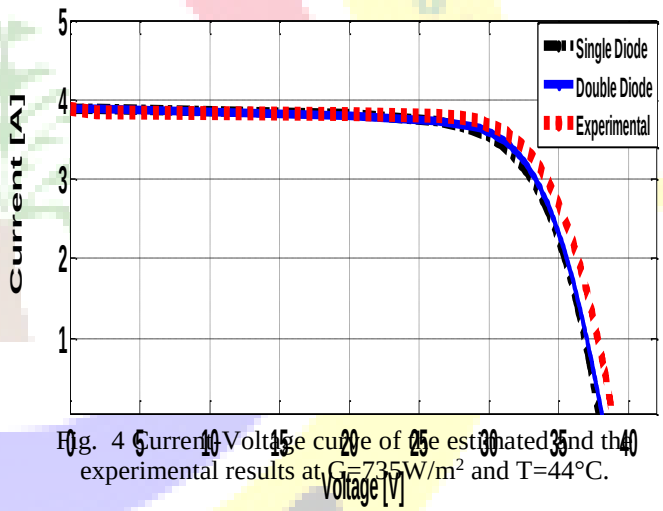

Fig. 4 Current-Voltage curve of the estimated and the experimental results at G=735W/m² and T=44°C.

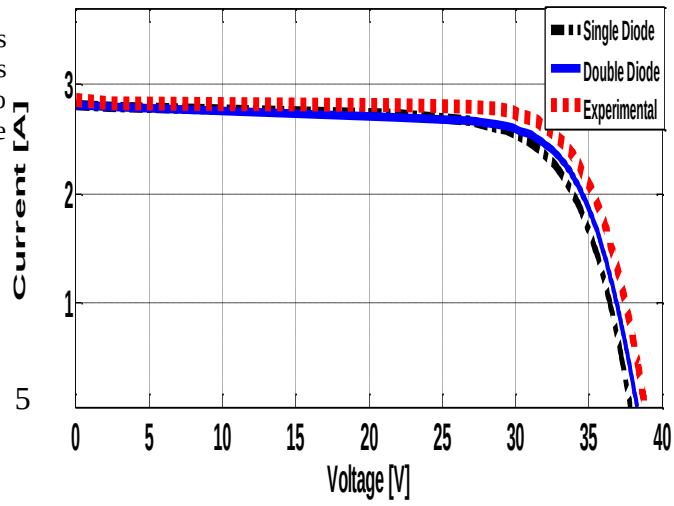

Fig. 5 Current-Voltage curve of the estimated and the experimental results at G=531W/m^2 and T=41°C.

Besides, observing the curves we see that, the estimated results are very close to the experimental results except at the knee of the curve where the experimental data a little far from both models results. The temperature effect is not very large in output power of the PV panel as it is the case in changing in the irradiance, where a small augmentation in the irradiance results a large augmentation in output current but not in open circuit voltage value.

Furthermore, RMSE and MBE% for each test are given in Table 5 and Table 6 respectively. The study shows that in last three testes Double diode model has better results. Best RMSE=0.197 in DDM compared to RMSE=0.405 in SDM, MBE%=0.125 in DDM compared to best MBE%=0.150 in SDM.

However, the estimated computation time in double diode model is large compared to single diode model (0.36 sec in DDM and 0.34 sec in SDM) that is because of the additional component used (recombination loss represented by the second junction diode). Therefore, for fast results one can use single diode model but for more accurate results double diode model is the one can be used.

TABLEV
TABLE OF RMSE VALUES AT DIFFERENT CASES OF IRRADIANCE AND CELL TEMPERATURE.

	G=1080 W/m^2 T=50°C	**G=735W/m^2 T=44°C**	**G=531W/m^2 T=41°C**	**G=362W/m^2 T=39°C**
Single Diode	0.769	0.578	0.488	0.405
Double Diode	0.820	0.460	0.292	0.197

TABLE VI
TABLE OF MBE% VALUES AT DIFFERENT CASES OF IRRADIANCE AND CELL TEMPERATURE.

	G=1080 W/m^2 T=50°C	**G=735W/m^2 T=44°C**	**G=531W/m^2 T=41°C**	**G=362W/m^2 T=39°C**
Single Diode	0.150	0.176	0.207	0.254
Double Diode	0.165	0.140	0.126	0.125

IX. CONCLUSION

Choosing the appropriate PV model is an important step to predict the behavior of the PV system, for that raison a comparison of the characterization for the PV Panel using single diode and double diode models have been done with an excremental validation. In our major tests (three of four tests) double diode model presents a better results (best RMSE=0.197 and MBE%=0.125 for double diode and best RMSE=0.405 and MBE%=0.15 for single diode). However the computation time needed in double diode model is large compared to the time needed in single diode. The estimated execution time in double diode is 1.058 times needed in single diode. In case of large system this difference in time could be a problem. So the selection of the model depends on the designer whether he needs fast results he can use the single diode model or for more accuracy he can use double diode model. This study was made under uniform incident irradiance, it will be interesting to find whether that results holds under partial shaded conditions as a future studies.

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