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Modeling and Simulation of Photovoltaic Cell/Module/Array with Two-Diode Model

Basim Alsayid

***Abstract*— The purpose of this paper is to propose a MATLAB/ Simulink simulators for PV cell/module/array based on the Two-diode model of a PV cell.This model is known to have better accuracy at low irradiance levels which allows for more accurate prediction of PV systems performance.To reduce computational time , the input parameters are reduced as the values of Rs and Rp are estimated by an efficient iteration method. Furthermore ,all of the inputs to the simulators are information available on a standard PV module datasheet. The present paper present first abrief introduction to the behavior and functioning of a PV device and write the basic equation of the two-diode model,without the intention of providing an indepth analysis of the photovoltaic phenomena and the semicondutor physics. The introduction on PV devices is followed by the modeling and simulation of PV cell/PV module/PV array, which is the main subject of this paper. A MATLAB Simulik based simulation study of PV cell/PV module/PV array is carried out and presented .The simulation model makes use of the two-diode model basic circuit equations of PV solar cell, taking the effect of sunlight irradiance and cell temperature into consideration on the output current I-V characteristic and output power P-V characteristic . A particular typical 50W solar panel was used for model evaluation. The simulation results , compared with points taken directly from the data sheet and curves pubblished by the manufacturers, show excellent correspondance to the model.**

***Index Terms*—Double Diode, Photovoltaic Cells/Modules/Arrays, Modeling, Two-diode.**

I. INTRODUCTION

A photovoltaic (PV) system directly converts sunlight into electricity. The basic device of a PV system is the photovoltaic (PV) cell. The photovoltaic module is the result of associating a group of PV cells in series and parallel and it represents the conversion unit in this generation system. An array is the result of associating a group of photovoltaic modules in series and parallel. The obtained energy depends on solar radiation, the temperature of the cell and the voltage produced in the photovoltaic module. The voltage and current available at the terminals of a PV device may directly feed small loads . More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and the current at the load mainly to track the maximum power point of the device [1], [2] ,[3], [4], [5].

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II. SOLAR CELL MODELING

The equivalent circuit model of a PV cell is needed in order to simulate its real behavior. One of the models proposed in literature is the two-diode model [12]. Using the physics of p-n junctions, a cell can be modeled as a DC current source in parallel with two diodes that represent currents escaping due to diffusion and charge recombination mechanisms. The consideration of the recombination loss leads to a more precise model known as two-diode model shown in figure 1 [13]. Two resistances, Rs and Rp, are included to model the contact resistances and the internal PV cell resistance respectively [1], [2] ,[3], [4], [8] . The values of these two resistances can be obtained from measurements or by using curve fitting methods based on the I-V characteristic of the cell. The curve fitting techniques is used here to approximate the values of Rs and Rp [4]. Assuming that the current passing in diode D2 due to charge recombination is small enough to be neglected, a simplified PV cell model can be reached as shown in fig. 2 known as single-diode model [11], [13], [14].

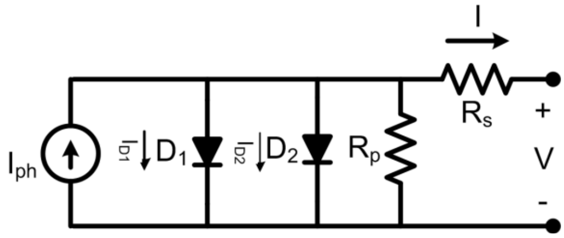

Fig. 1: Equivalent Model of Two-Diode Photovoltaic Cell.

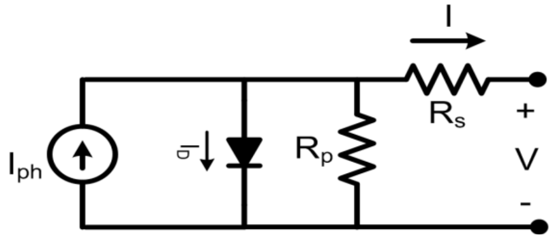

Fig. 2 : Equivalent Model of Single-Diode Photovoltaic Cell.

The relationship between the PV cell output current and terminal voltage according to the single-diode model is governed by equation (1), (2) and (3):

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

$$I_D = I_0 \left[\exp\left(\frac{q * V}{\alpha * k * T} \right) - 1 \right] \quad (2)$$

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$$I = I_{PH} - I_0\left[\exp\left(\frac{q*V}{\alpha*k*T}\right)-1\right] \quad (3)$$

The basic equation (3) of the elementary PV cell does not represent the I-V characteristic of practical ones. Practical modules are composed of several connected PV cells which requires the inclusion of additional parameters, Rs and Rp, with these parameters equation (3) becomes equation (4)

$$I = I_{PH} - I_0\left[EXP\left(\frac{V+R_S*I}{Vt*\alpha}\right)-1\right]-\frac{V+R_S*I}{R_P} \quad (4)$$

The basic equation (3) of the two-diode model of the PV cell is the following equation (5)

$$I = I_{PH} - I_{D1} - I_{D2} \quad (5)$$

Equation (6) and (7) are of I_{D1} and I_{D2}

$$I_{D1} = I_{01}\left[\exp\left(\frac{q*V}{\alpha 1*k*T}\right)-1\right] \quad (6)$$

$$I_{D2} = I_{02}\left[\exp\left(\frac{q*V}{\alpha 2*k*T}\right)-1\right] \quad (7)$$

After the combination of equation (6) and (7), equation (5) becomes equation (8)

$$I = I_{PH} - I_{01}\left[EXP\left(\frac{V+R_S*I}{Vt*\alpha 1}\right)-1\right]- I_{02}\left[EXP\left(\frac{V+R_S*I}{Vt*\alpha 2}\right)\right]-\frac{V+R_S*I}{R_P} \quad (8)$$

Where :

- I_{PH} is the current generated by the incident light .
- I_{D1} is the Shockley diode equation due to diffusion.
- I_{D2} is the Shockley diode equation due to charge recombination mechanisms.
- I_0[A] is the reverse saturation current of the diode D [A].
- I_{01}, I_{02} [A] are the reverse saturation current of the diodes D1 and D2 respectively.
- q is the electron charge [1.60217646 · 10^{-19}C].
- k is the Boltzmann constant [1.3806503 · 10^{-23}J/K].
- T [K] is the temperature of the p-n junction.
- α is the diode D ideality factor.
- $\alpha 1$=1 is the diode D1 ideality factor.
- $\alpha 2 \geq$ 1.2 is the diode D2 ideality factor
- $Vt = N_S*k*T/q$ is the thermal voltage of the module with Ns cell connected in series.

The light-generated current of the module depends linearly on solar irradiation and is also influenced by temperature according to equation (9)

$$I_{PH} = \left(I_{PH,n} + K_I\Delta T\right)\frac{G}{G_n} \quad (9)$$

Where $I_{PH,n}$ is the light-generated current of the module at standard test condition given by equation (22). The diode saturation current I_0 dependence on temperature can be expressed as shown in equation (10).

$$I_0 = I_{0,n}\left(\frac{T_n}{T}\right)^3 EXP\left[\frac{q*E_g}{\alpha*k}\left(\frac{1}{T_n}-\frac{1}{T}\right)\right] \quad (10)$$

E_g is the band gap energy of the semiconductor and $I_{0,n}$ is the nominal saturation current expressed by equation (11) at standard test conditions (STC)

$$I_{0,n} = \frac{I_{SC,n}}{\left[EXP\left(\frac{V_{OC,n}}{V_{t,n}*\alpha}\right)-1\right]} \quad (11)$$

From equation (10) and (11) I_0 can be expressed as shown in equation (12)

$$I_0 = \frac{I_{SC,n}+K_I\Delta T}{EXP\left(\frac{V_{OC,n}+K_V\Delta T}{Vt*\alpha}\right)-1} \quad (12)$$

Where $V_{OC,n}$ is open circuit voltage, $I_{SC,n}$ is the short circuit current, $V_{t,n}$ is the thermal voltage and G_n is the irradiance, T_n is the temperature, all at standard test conditions, K_V is the open circuit voltage temperature coefficient , K_I is the short circuit temperature coefficient [6], [7]. To simplify the model, in this work, both of the reverse saturation currents, I_{01} and I_{02} are set to be equal :

$$I_{01} = I_{02} = \frac{I_{SC,n}+K_I\Delta T}{EXP\left(\frac{V_{OC,n}+K_V\Delta T}{Vt*(\alpha 1+\alpha 2)/p}\right)-1} \quad (13)$$

The diode ideality factors $\alpha 1$ and $\alpha 2$ represent represent the diffusion and recombination currents. In accordance with Shockley's diffusion theory, $\alpha 1$ must be unity [9], [10]. The value of $\alpha 2$ is flexible. The value of $\alpha 2$ is flexible. Based on the simulation results, it was found that if $\alpha 2 \geq 1.2$, the best match between the proposed model and the practical I-V curve is obtained. Since $(\alpha 1+\alpha 2)/p = 1$ and $\alpha 1 = 1$, it follows that the variable p can be chosen to be ≥2.2. With these considerations equation (13) becomes equation (14) [9].

$$I_{01} = I_{02} = \frac{I_{SC,n}+K_I\Delta T}{EXP\left(\frac{V_{OC,n}+K_V\Delta T}{Vt}\right)-1} \quad (14)$$

Cells connected in parallel increase the current and cells connected in series provide greater output voltages. If the module is composed of N_p parallel connections of cells the photovoltaic and saturation currents may be expressed as:

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$I_{PH,module}=I_{PH} * N_p$, $I_{0,module}=I_0 * N_p$.

In equation (8) R_s is the equivalent series resistance (unknown) and R_p is the equivalent parallel resistance (unknown), so they have to be calculated by iteration. Equation (8) originates the I-V curve seen in fig. 3, where three remarkable points are highlighted and will be taken for comparison between simulation results and experimental values given in data sheet, these points are:

a) open- circuit voltage (*Voc*, 0).
b) short circuit current (0, *Isc*).
c) maximum power point (*Vmp, Imp*).

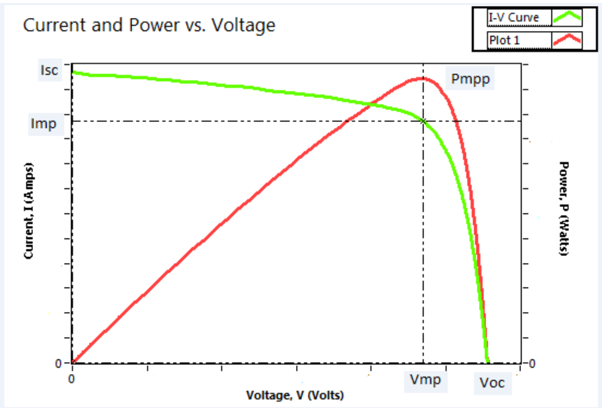

Fig. 3: Characteristic Current (I)-Voltage (V), Power (P)-Voltage (V) curve of a practical photovoltaic device with the three remarkable points.

a) Open-circuit voltage: this point is obtained when the terminals of the module are disconnected. The module presents a voltage called (V_{OC}) expressed analytically using equation (15).

$$V_{OC} = \frac{\alpha * k * T}{q} \ln \frac{I_{PV}}{I_0} \quad ; I_{PV} > I_0 \qquad (15)$$

b) Short-circuit current**:** the terminals of the module are connected with an ideal conductor, through which flows a current called (I_{SC}). In this situation, the voltage between module terminals is zero.

$$I_{SC} = I_{PH} = K * G \qquad (16)$$

where K is a constant and G is the irradiance (W/m²).

c) P_{MPP} where the voltage versus current product is maximum which means maximum power. V_{MP} is related to V_{OC} through the relation (17) :

$$V_{MP} \approx 0.8 * Voc \qquad (17)$$

And I_{MP} is related to I_{SC} through the relation (18) :

$$I_{MP} \approx 0.9 * I_{SC} \qquad (18)$$

The best conditions, are the "standard test conditions " happen at Irradiance equal to 1000W/m², cells temperature equals to 25°C, and spectral distribution (Air Mass) AM is equal to 1.5.

III. MODELING OF PHOTOVOLTAIC MODULE

MSX-50 solar array PV module, pictured in fig. 4, is chosen for a MATLAB simulation model. The module is made of 36 multi-crystalline silicon solar cells in series and provides 50W of nominal maximum power. Table 1 shows its electrical specification and fig. 5 shows its I-V characteristics from data sheet for different temperatures.

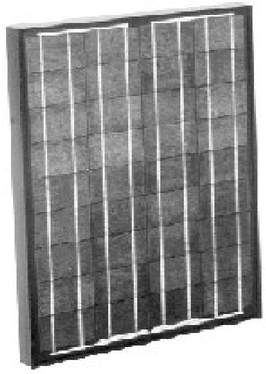

Fig. 4: Picture of MSX-50 Photovoltaic Module

Table I: Electrical characteristics data of the MSX-50 solar at 25 °C, 1.5AM, 1000W/m^2. taken from the datasheet

Electrical Characteristics	
Maximum Power (Pmax)	50W
Voltage at Pmax (Vmp)	17.1V
Current at Pmax (Imp)	2.92A
Open-circuit voltage (Voc)	21.1V
Short-circuit current (Isc)	3.17A
(K_I)Temperature coefficient of Isc	(0.0032±0.015)%/°C
(K_V) Temperature coefficient of Voc	– (80±10)mV/°C
NOCT	47±2°C

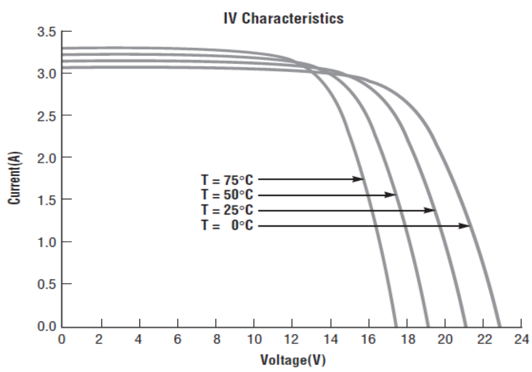

Fig. 5: Current (I)-Voltage (V) characteristics at 1000W/m^2 ,from data sheet with different temperatures.

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IV. RS AND RP CALCULATION

Rs and Rp are calculated iteratively. The goal is to find, applying equation (20), the values of Rs and Rp that makes the mathematical Power-Voltage curve peak coincide with the experimental peak power at the (*Vmp, Imp*) point by iteratively increasing the value of Rs while simultaneously calculating the value of Rp with equation (21). The initial conditions for Rs and Rp are shown in equation (21). The value of Rs and Rp are reached when the iteration stopped for $P_{max,m}$ calculated is equal to $P_{max,e}$ experimental from data sheet . The simplified iteration flowchart is illustrated in Fig. 6 [4], [9]. The iterative method gives the solution Rs = 0.416 Ω and Rp=180.8749 Ω.

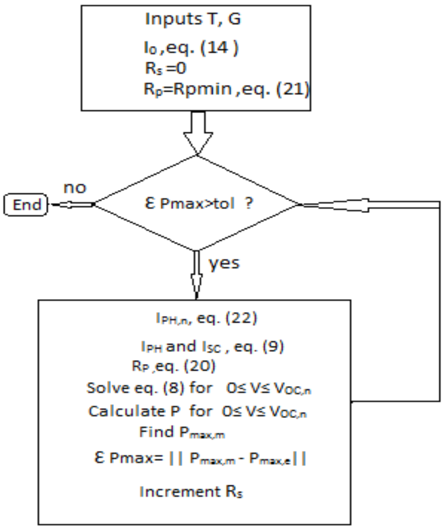

Fig. 6: Simplified flowchart of the iteration used for Rs and Rp calculation.

$$P_{\max,m} = V_{MP}\left\{I_{PH} - I_0\left[\exp\left(\frac{q*(V_{MP}+R_S*I_{MP})}{\alpha 1*k*T*N_S}\right)-1\right] - \frac{V_{MP}+R_S*I_{MP}}{R_P}\right\} = P_{\max,e} \quad (19)$$

$$R_P = \frac{V_{MP}(V_{MP}+I_{MP}*R_S)}{V_{MP}*I_{HP} - V_{MP}*I_0\left[\frac{(V_{MP}+I_{MP}*R_S)*q}{N_S*\alpha*k*T}\right] + V_{MP}*I_0 - P_{\max,e}} \quad (20)$$

$$Rs = 0; Rp\min = \frac{V_{MP}}{I_{SC,n}-I_{MP}} - \frac{V_{OC,n}-V_{MP}}{I_{MP}} \quad (21)$$

$$I_{PH,n} = \frac{(R_S+R_P)}{R_P} * I_{SC,n} \quad (22)$$

Fig. 7 Shows the I –V curve at standard conditions where the three remarkable points, maximum power point (V_{MP}, I_{MP}), open circuit voltage point (V_{OC} ,0) and (0, I_{SC}) point values are shown after the calculation of Rs and Rp by curve fitting with iteration. The model curves exactly match with the experimental data at the three remarkable points provided by the data sheet in table I.

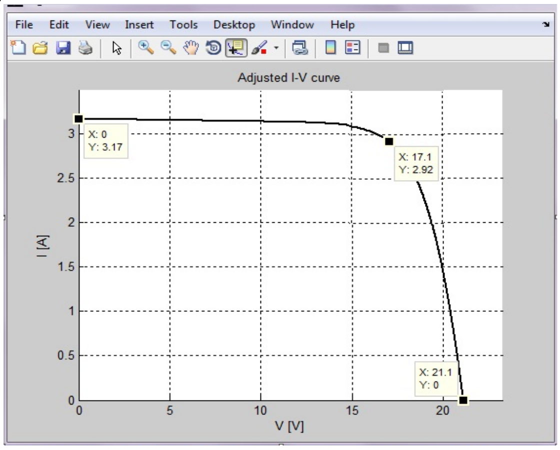

Fig. 7: Current (I)-Voltage (V) curve at standard conditions, Temperature (T)=25° , irradiance (G) =1000Watt/m², after calculation of Rs and Rp with iterative method.

V. SIMULATION IN MATLAB/SIMULINK

A. PV Module Simulation

The block diagram in fig. 8 is simulated using Matlab /simulink for obtaining the module characteristics with different irradiances and temperatures. The modeling of the PV is done applying the equations seen before, (4) ,(5), (6) ,(7), (8) , (9),(10) and (14). Two types of simulation are carried out:

First the temperature is maintained constant at 25° C and varying irradiance (1000W/m^2 ,800 ,600 ,400,200) will generate the characteristic curves. Fig. 9 shows the simulation results under these conditions on current (I)-Voltage (V) characteristics which are very closed to the real data. It is clear that current generated by the incident light depends on irradiance, the higher the irradiance, the greater the current. On the other hand, voltage is staying almost constant and it is not going to vary much. Fig. 10 shows the simulation results under the same conditions on Power-Voltage characteristics which are very closed to the real data. The influence of irradiation on maximum power point is clear, the higher the irradiance, the major the maximum power point will be. In fig. 7 the three remarkable points *Voc=21.1V, Isc=3.17A* and maximum power point (Pmax=50W,V_{MP}=17.1V, I_{MP}= 2.92 A) are shown and are identical to the values given by the datasheet.

Second the irradiance is maintained constant at 1000W/m^2 and varying temperature (25° C, 50° C, 75° C) will generate the characteristic curves. Fig. 11 show the simulation results of current (I)-Voltage (I) characteristic under these conditions. The curves are very closed to the curves given by data sheet shown in fig. 5. The current generated by the incident light is going to stay constant although it increases slightly while the voltage decreases. Fig. 12 shows the simulation results under the same conditions on Power (P)-Voltage (V) characteristics and are very closed to the real data. The effect of the temperature increase, decreases voltage and power.

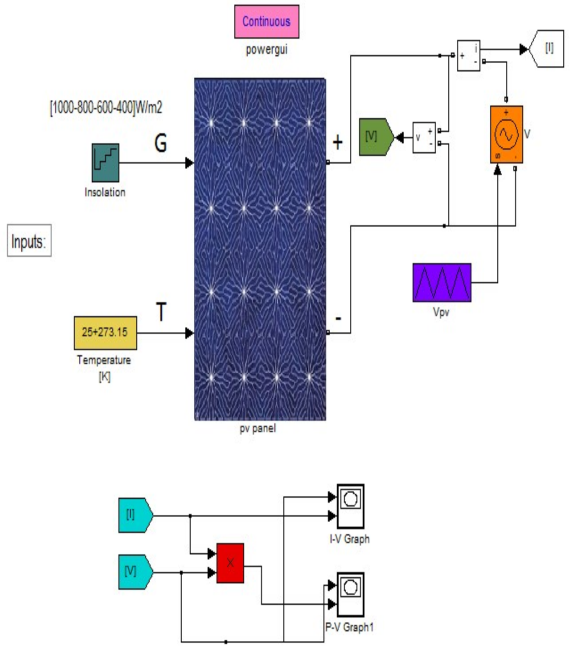

Fig. 8: PV module model in Simulink

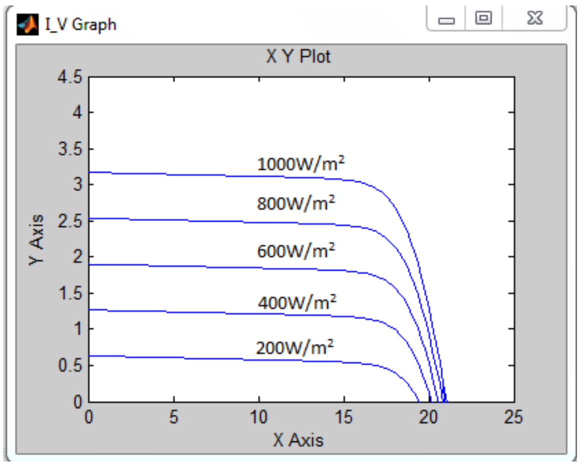

Fig. 9: Current (I)-Voltage (V) curve at temperature (T)=25°C for different irradiances.

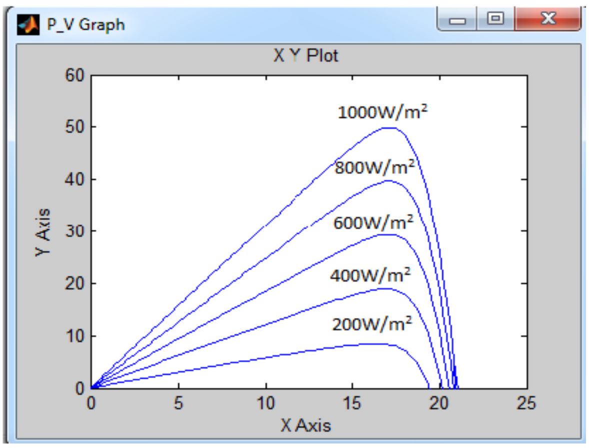

Fig. 10: Power (P)-Voltage (V) curve at Temperature (T)=25°C with different irradiances.

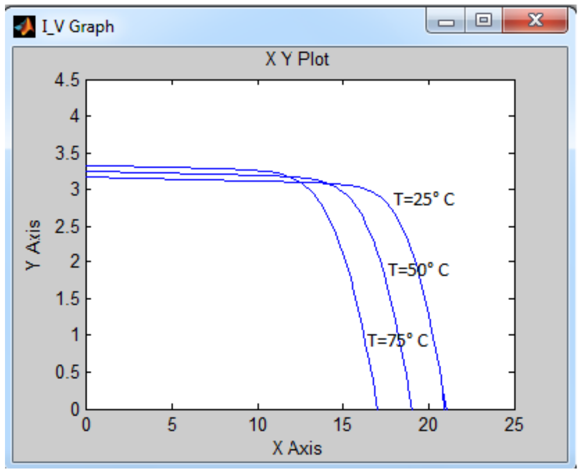

Fig. 11: Current (I)-Voltage (V) curve at irradiance (G)=1000Watt/m^2 for different Temperatures.

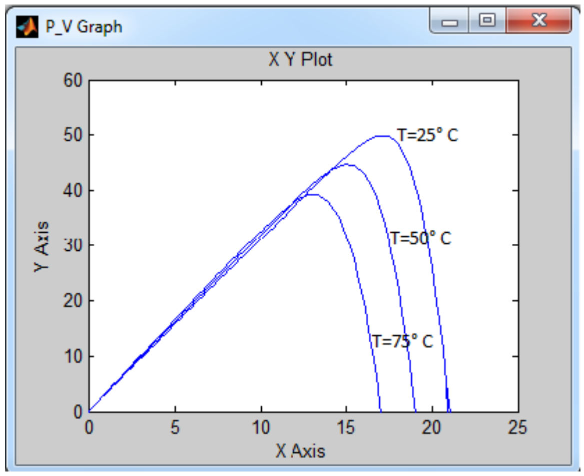

Fig. 12: Power (P)-Voltage (V) curve at irradiance (G)=1000W/m^2 for different Temperatures.

B. PV Array Simulation

Modules connected in parallel increase the current and modules connected in series provide greater output voltages. If the array is composed of N_{par} parallel connections of PV modules, the photovoltaic and saturation currents may be expressed as [12]:

$I_{PH}=I_{PH,\ module} * N_{par}$, $I_0=I_{0,\ module} * N_{par}$.

If the array is series connected with *Nser* module, the output voltage is :

$V=V_{module} * Nser$,

$Rs,array=Rs,module*(N_{ser}/N_{par})$,

$Rp,array = Rp,module *(N_{ser}/N_{par})$.

The model of the array will be as shown in fig. 13. If we take as an example *Nser=2* and *Npar=15*, just to verify the validation of the array model we will have the results of simulation shown in fig. 14 for current (I)-Voltage (V) characteristic at T=25°C .The *Isc=6.34A (3.17A* 2)* as expected for *Npar=2*, *Voc=316.5V (21.1V*15)* as expected for *Nser=15* . Fig. 15 shows Power (P)-Voltage (V) characteristic for the same conditions where the value of the peak power is as expected to be 1500W=(15*2*50W).

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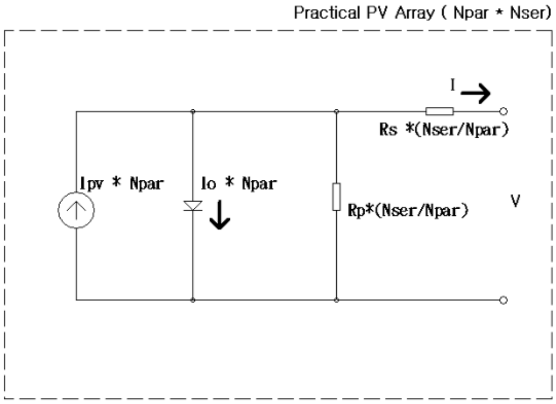

Fig. 13: PV array model , *Nser* is No. of series pv modules, *Npar* is No. of parallel pv modules.

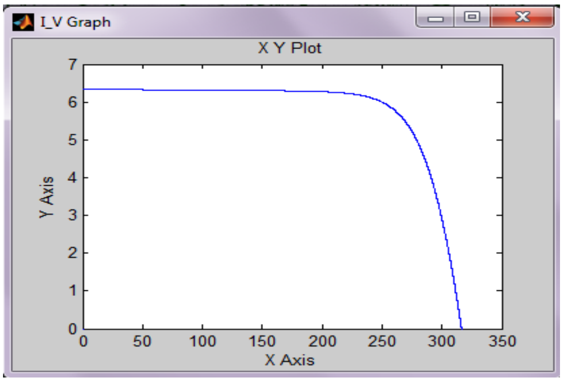

Fig. 14: Current (I)-Voltage (V) characteristics at Temperature (T)=25°C, irradiance (G) =1000Watt/m^2 ,by Simulink for Nser=15,Npar=2.

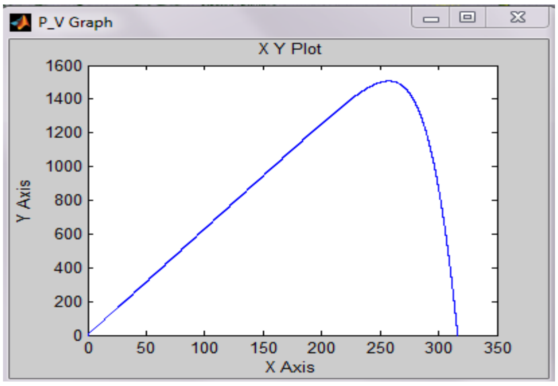

Fig. 15: Power (P)-Voltage (V) characteristics at Temperature (T)=25°C, irradiance (G)=1000W/m^2 ,by Simulink for *Nser=15, Npar=2*

VI. CONCLUSION

In this paper, a MATLAB/Simulink PV system simulator based on an improved two-diode model is proposed. To reduce the computational time, the input parameters are reduced as the values of Rp and Rs are estimated by an efficient iteration method. Furthermore the inputs to the simulator are information available on standard PV module datasheets. Simulation results show excellent correspondence to manufacturers published curves in data sheet.

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VII. AUTHOR’S PROFILE

Dr. Basim Alsayid received B.Sc. in Electrical Engineering from Studies University of Bologna, Bologna, Italy in 1991. He received his Ph.D.Degree in Electrical Drives Engineering from University of Bologna, Bologna in 2002. From 2002 to 2007 he worked as Assistant professor in in the Department of Electrical Engineering ,Palestine Technical University (Kadoorie) ,Tul Karm – Palestine. From 2007 to 2009 he worked as the head of the electrical engineering department and from 2009 till now he is the dean of the college of engineering and technology at the same university.He is a member of IEEE, Palestinian Engineers Association . he is now involved in a 2 years research program about design and control of photovoltaic systems with a French research group.