Extraction of the unknown Parameters of a Photovoltaic Module from Manufacture Data Sheet

Mokhtar Said El-Negamy, Abeer Galal, G.M. El-Bayoumi

Abstract*— This paper represents an approach to identify the parameters of the equivalent circuit of a photovoltaic (PV) module and other parameters that are needed to determine the performance characteristics of the module. The proposed approach is based on the remarkable points given by the manufacture datasheet and considering the effect of irradiance and temperature change on the PV module characteristics. The implementation of this method in MATLAB® script provides the model parameters which have to minimize as soon as possible the error involved between the calculated and measured output current. The proposed approach explains the relation which governs the exchange in the series resistance, shunt resistance, the light photo current, and the maximum power of the PV module due to the variation of the cell temperature. The used model is implemented as a MATLAB® script which yields the I-V and P-V characteristics of the PV panel under variations of cell temperature and solar irradiance. The formulated model results were validated with rated power output of a photovoltaic module provided by manufacturers using local meteorological data, which gave $\pm 0.1688\%$ error for MSP290AS module and $\pm 0.156\ \%$ error for MSMD290AS module at standard test condition. It is found that the proposed model is more practical in terms of precise estimations of photovoltaic module power output for any required location and number of variables used.

***Index Terms*— Photovoltaic model, Parameters Estimation, manufacture data.**

I. INTRODUCTION

Electricity production by renewable energy sources is actually promoted in many countries worldwide and is considered a strategic objective for the next years. Many founding programs also support projects that provide potential utilities with access to renewable energy solutions and increase familiarity with renewable energy technologies. For these reasons, it is mandatory to improve the know-how and skills in this field. Nowadays there is a lot of concern about photovoltaic systems because they can generate electricity on-site where it is needed, avoiding transport losses and contributing to CO2 emission reductions in urban Centre's [1]. Knowledge of the characteristic of a PV panel is a prerequisite for designing and sizing a PV power supply.it is possible to develop simulations based on models of the PV panel. After the model has been estimated in given experimental conditions, it can be used to predict the PV panel operation under different working conditions (i.e. surface temperature of the PV panel, irradiance and weather conditions) [1].

The simulation procedure can simulate steady-state and/or transient conditions so it is possible to focus the analysis on feasibility studies or on short-time performances. The simulation tool gives also the advantage of simulating different PV array sizes and the possibility to arrange virtually the panels or arrays as a network to analyze the behavior and performances of a plant in a lot of possible configurations [1]. The PV model has five unknown parameters, which are I_{ph},I_o, a, R_s and R_{sh} . These parameters are not given in the manufacturer datasheet. Many researchers tried to estimate these unknown parameters. Abdel-Halim (2004) didn't consider R_{sh} and a, and built his model on a simple equivalent circuit. Villalva et. al., (2009) did a nice work by approximating the PV model based on remarkable points and estimated the unknown parameters. Chatterjee *et. al.*(2011), approximated the PV module characteristics given in (1) by neglecting the term (-1), then form five equations and solve it simultaneously, which is tedious effort. Farivar et. al., (2010) formed five equations based on Fill Factor and normalized resistances and obtained a good results. Katsanevakis (2011), represented the PV model using 3 different types of equivalent circuits and selected the accurate one. Carlos de Manuel (2014), represented estimation of the parameters based on the lambert W-function [26-31, 39].

In this paper, the unknown parameters are determined using the measured data given in the datasheets. Then using the basic equations that relate the voltage, current and power of the PV module, the unknown parameters can be identified. Unlike other methods, the proposed method is straightforward and does not need any additional information more than the manufacturer datasheet. In the selected model the effect of temperature coefficients is also considered. By using the proposed approach, PV system designers and researchers would be able to model the PV arrays without any considerable effort.

II. FORMULATED MODEL FOR COMPUTING CURRENT OUTPUT OF PV MODULES

As it is well known, ideal solar cells behave like a current source connected in parallel with a diode [2-4]. This ideal model is completed with resistors to represent the losses and sometimes with additional diodes that takes into account other phenomena [5,6]. The most popular circuit equivalent to a solar cell/panel is shown in Figure 1; it includes a current source, one diode and two resistors: one in series and one in parallel [7-14]. Each element included in the equivalent circuit implies one parameter that has to be determined. Therefore, five parameters need to be calculated when using this method [15-25]. The current-voltage curve of a solar cell or panel is shown in Figure 2, is quite well reproduced by this simple equivalent circuit.

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Three points of the *I-V* curve are also indicated in this Figure 2: short circuit, maximum power, and open circuit points. These representative points are, together with their variation as a function of the temperature, the normal information included in manufacturers' datasheets.

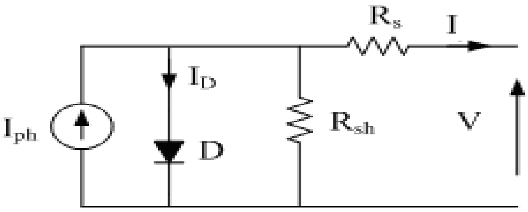

Figure 1. Equivalent circuit of a solar panel.

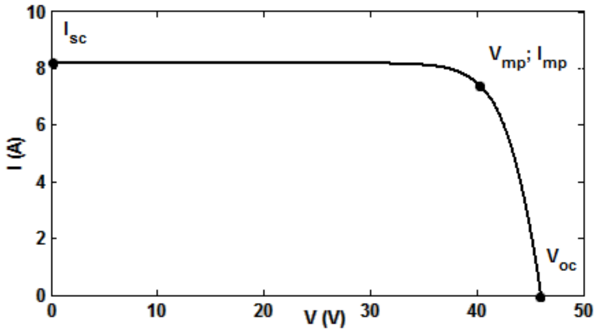

Figure 2. I-V curve of a solar panel. The three characteristic points (short circuit, maximum power, and open circuit points) are indicated on the curve.

$$I = I_{ph} - I_D - I_{sh} \tag{1}$$

Where, I_{sh} is the shunt-resistance current and is given by:

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \tag{2}$$

Where V is the terminal voltage of the PV module

Also I_D is the diode current and is given by:

$$I_D = I_o\left[e^{\frac{(V+IR_s)}{aV_T}} - 1\right] \tag{3}$$

Where I_o is the reverse saturation current,

a is an empirical non-ideality factor for the diode

V_T is the junction thermal voltage and is given by:

$$V_T = \frac{N_s K T_c}{q} \tag{4}$$

Where N_s is the series-connected solar cells per module,

q is the electron charge = 1.60217646×10^{-19} C ,

k is Boltzmann constant = 1.3806503×10^{-23} J/K ,

T_c is the absolute cell temperature in Kelvin.

Substituting the shunt resistance current and diode current values in equation (1), then

$$I = I_{ph} - I_o\left[e^{\frac{(V+IR_s)}{aV_T}} - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{5}$$

Generally, the manufacturers of PV modules provide information at certain points on the PV characteristic; such as the short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and the maximum power point current (I_{mp}) and voltage (V_{mp}), which are called remarkable points. Moreover, the temperature coefficients for I_{sc} and V_{oc} are also provided in the manufacturer sheet as K_i and K_v respectively. Always K_i is positive temperature coefficient, but K_v is negative temperature coefficient. Also the number of series-connected cells per module (N_s) is provided.

III. PROPOSED APPROACH

The main idea of the proposed method is to form four equations as functions of the four unknown I_{ph}, I_o, R_s **and** R_{sh}, considering the parameter *a* can be obtained around the value listed in table 1, that relates the value of *a* with the PV technology [31].

Table 1. Diode non-ideality factor (*a*) corresponding to PV

Technology	*a*
Si-mono	1.2
Si-poly	1.3
a-Si:H tandem (single junction)	1.8
a-Si:H tandem (double junction)	3.3
a-Si:H triple (triple junction)	5.0
CdTe	1.5
CIS	1.5
AsGa	1.3

In order to obtain the four unknown, equation (1) is considered as the backbone to form the four proposed equations at the remarkable points as follows:

Open-Circuit Voltage Voc

If the terminals of the PV model are left open, then there is no output current (I=0). Then substituting with (I=0) in equation (5) to obtain the open-circuit voltage:

$$0 = I_{ph} - I_o\left[e^{\frac{(V_{oc})}{aV_T}} - 1\right] - \frac{V_{oc}}{R_{sh}} \tag{6}$$

Assume $\gamma = e^{\frac{V_{oc}}{aV_T}}$ and substitute in above equation then rearrange it,

$$R_{sh} = \frac{V_{oc}}{I_{ph} - I_o(\gamma - 1)} \tag{7}$$

Short-Circuit Current Isc

If the terminals of the PV module circuit are shorted (V=0), The short circuit current can be obtained by substituting V=0 in equation (5):

$$I_{sh} = I_{ph} - I_o\left[e^{\frac{(I_{sc}R_s)}{aV_T}} - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \tag{8}$$

Assume $\alpha = e^{\frac{I_{sh}R_s}{aV_T}}$ and substitute in above equation then rearrange it,

$$I_{ph} = I_{sc}\left(1 + \frac{R_s}{R_{sh}}\right) + I_o(\alpha - 1) \tag{9}$$

Maximum Power Point

To obtain the maximum power condition, we can replace the module voltage and current given in equation (5) with those at maximum power point that is V_{mp} and I_{mp}, respectively. Then the maximum current will be:

$$I_{mp} = I_{ph} - I_o\left[e^{\frac{(V_{mp}+I_{mp}R_s)}{aV_T}} - 1\right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{10}$$

Assume $\beta = e^{\frac{V_{mp}+I_{mp}R_s}{aV_T}}$ and substitute in above equation then rearrange it,

$$I_o = \frac{I_{ph} - I_{mp}\left(1 + \frac{R_s}{R_{sh}}\right) - \frac{V_{mp}}{R_{sh}}}{(\beta - 1)} \tag{11}$$

To obtain the maximum power (P_{max}) , we can multiply both sides of equation (10) by V_{mp} and rearrange it:

$$P_{max}\left(1+\frac{R_s}{R_{sh}}\right)=V_{mp}\left[I_{ph}-I_o(\beta-1)\right]-\frac{{V_{mp}}^2}{R_{sh}} \qquad (12)$$

Knowing that the derivative of P_{max} w.r.t. V_{mp} is zero then:

$$V_{mp}\left(\frac{I_o\beta}{aV_T}+\frac{2}{R_{sh}}\right)-\left(I_{ph}-I_o(\beta-1)\right)=0 \qquad (13)$$

Solving (7), (9),(11) and (13) simultaneously, the four unknown of any PV module can be obtained easily.

A. Proposed Solution

The unknown I_{ph}, I_o, **and** R_{sh} that are represented by (7), (9) and (11), respectively, will be expressed as a function of R_s only. Then their values will be substituted in (13).
Substitute from (7) in (9), and assuming that

$$\theta=\frac{I_{sc}R_s}{V_{oc}}$$

An expression for I_{ph} can be obtained as:

$$I_{ph}=\frac{I_{sc}+I_o\left(\theta(1-\gamma)+(\alpha-1)\right)}{1-\theta} \qquad (14)$$

Substitute from (7) into (11), and assuming that

$$\Phi=\frac{V_{mp}+I_{mp}R_s}{V_{oc}}$$

An expression for Im can be obtained as:

$$I_{mp}=I_{ph}(1-\Phi)+I_0\left(\Phi(\gamma-1)-\beta+1\right) \qquad (15)$$

Substitute from (14) into (15), we can find an expression for Io as a function of R_s:

$$I_o=\frac{I_{sc}(1-\Phi)-I_{mp}(1-\theta)}{\beta(1-\theta)-\alpha(1-\Phi)+\gamma(\theta-\Phi)} \qquad (16)$$

Assuming that;

$$x=I_{sc}(1-\Phi)-I_{mp}(1-\theta)$$
$$y=\beta(1-\theta)-\alpha(1-\Phi)+\gamma(\theta-\Phi)$$

Substituting from (16) into (14), we can obtain an expression for I_{ph} as a function of Rs

$$I_{ph}=\frac{I_{sc}}{1-\theta}-\frac{x(\theta\gamma-\theta-\alpha+1)}{y(1-\theta)} \qquad (17)$$

Substituting from (16) and (17) into (7), we can obtain an expression for R_{sh} as a function of R_s

$$R_{sh}=\frac{yV_{oc}(1-\theta)}{yI_{sc}+x(\alpha-\gamma)} \qquad (18)$$

Substituting from (16), (17) and (18) into (13), we can get one equation in one variable that is R_s as:

$$x\beta\left(1+\frac{V_{mp}}{aV_T}\right)(V_{oc}-I_{sc}R_s)-2x\gamma V_{mp}+x\left(2\alpha V_{mp}+\gamma I_{sc}R_s-\alpha V_{oc}\right)+\frac{I_{sc}(2V_{mp}-V_{oc})}{V_{oc}}\left\{R_s\left(\alpha I_{mp}-\gamma I_{mp}+\gamma I_{sc}-\beta I_{sc}\right)+V_{mp}(\alpha-\gamma)+V_{oc}(\beta-\alpha)\right\}=0 \qquad (19)$$

Once the value of R_s is obtained, the other three unknown can be obtained based on (16), (17) and (18).

IV. RESULTS AND VERIFICATION

In this Section, the equivalent circuits of two commercial solar panels (MSP290AS 36.EU and MSMD290AS-36 by München Solar energie GmbH), are calculated as an example of application of the above method. For that calculation only data provided by the manufacturer is used see Table1 [32,33]. Based on the proposed approach described in section 2, and at non-ideality factor equal to 1.1, the unknown parameters of photovoltaic modules obtained at AM1.5g (1000W/m²) , T_r = 25°C and T_c =25°C in the two cases are included in Table 2.

Table 1. Characteristic points of MSP290AS-36.EU and MSMD290AS-36.EU modules included in the manufacturer datasheets at STC (1000W/m² irradiance, 25˚C cell temperature, AM1.5g spectrum according to EN 60904-3).

MSP290AS-36. EU(multicrystalline)		MSMD290AS-36.E U(monocrystalline)	
I_{sc}	8.37	I_{sc}	8.24
V_{oc}	44.32	V_{oc}	44.68
I_{mp}	7.82	I_{mp}	7.7
V_{mp}	37.08	V_{mp}	37.66
P_{mp}	290	P_{mp}	290
N_s	72	N_s	72

Table 2:- Parameters of MSP290AS-36.EU and MSMD290AS-36.EU solar panels equivalent circuits at STC (1000W/m² irradiance, 25˚C cell temperature, AM1.5g spectrum).

MSP290AS-36.EU (multicrystalline)			MSMD290AS36.EU (monocrystalline)	
a	1.1		a	1.1
I_{ph}	8.374417		I_{ph}	8.243520
I_o	2.880599× 10^{-9}		I_o	2.374480×10^{-9}
R_s	0.153148		R_s	0.122894
R_{sh}	290.205428		R_{sh}	287.654251

In order to spread the use of the equivalent circuit to any temperatures inside the range 10ºC to 55ºC (this bracket includes most of the operational temperatures; it should be taken also into account that the temperature of the panel is higher than the ambient temperature during operation), the process is repeated for temperatures in that range. Parameter values, showing their variation with temperature, are shown in Figures 3 for MSP290AS-36.EU(multicrystalline) and Figure 4 for MSMD290AS36.EU(monocrystalline). In the figure it can be observed how parameter *Rs* turns negative for high temperatures (the value of parameter *Rsh* could also turn negative under some conditions). Obviously, these solutions are mathematically valid but they are not physically possible. Possible solutions from the physics point of view only exist for certain values of the parameter *a*. For some panels it is difficult to find physically valid solutions (regarding resistor parameters *Rs* and *Rsh*) at any temperature and with constant *a*. This is because *a*, in reality, is not completely independent from temperature.

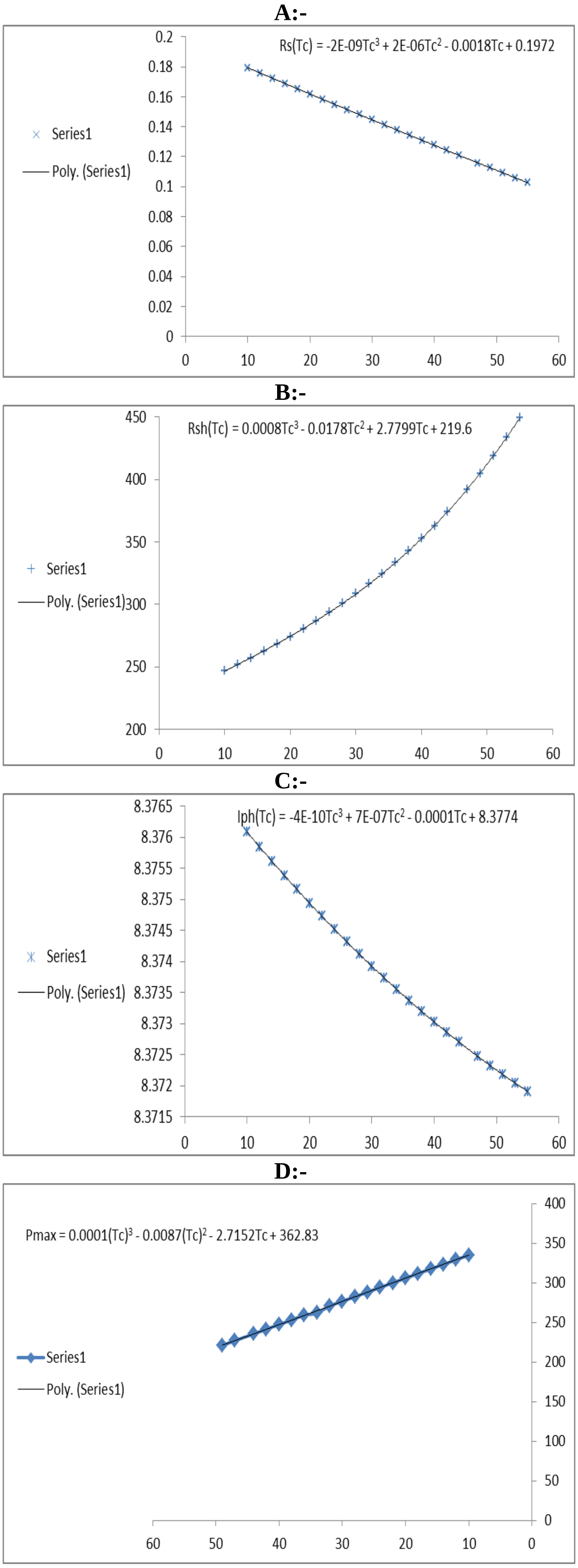

Figure 3. variation of parameters for MSP290AS-36.EU(multicrystalline) with temperature(a) Calculated $R_s(T_c)$ and polynomial regression. (b) Calculated $R_{sh}(T_c)$ and polynomial regression. (c) Calculated $I_{ph}(T_c)$ and polynomial regression.(d) Calculated maximum power P_{max} (T_c)

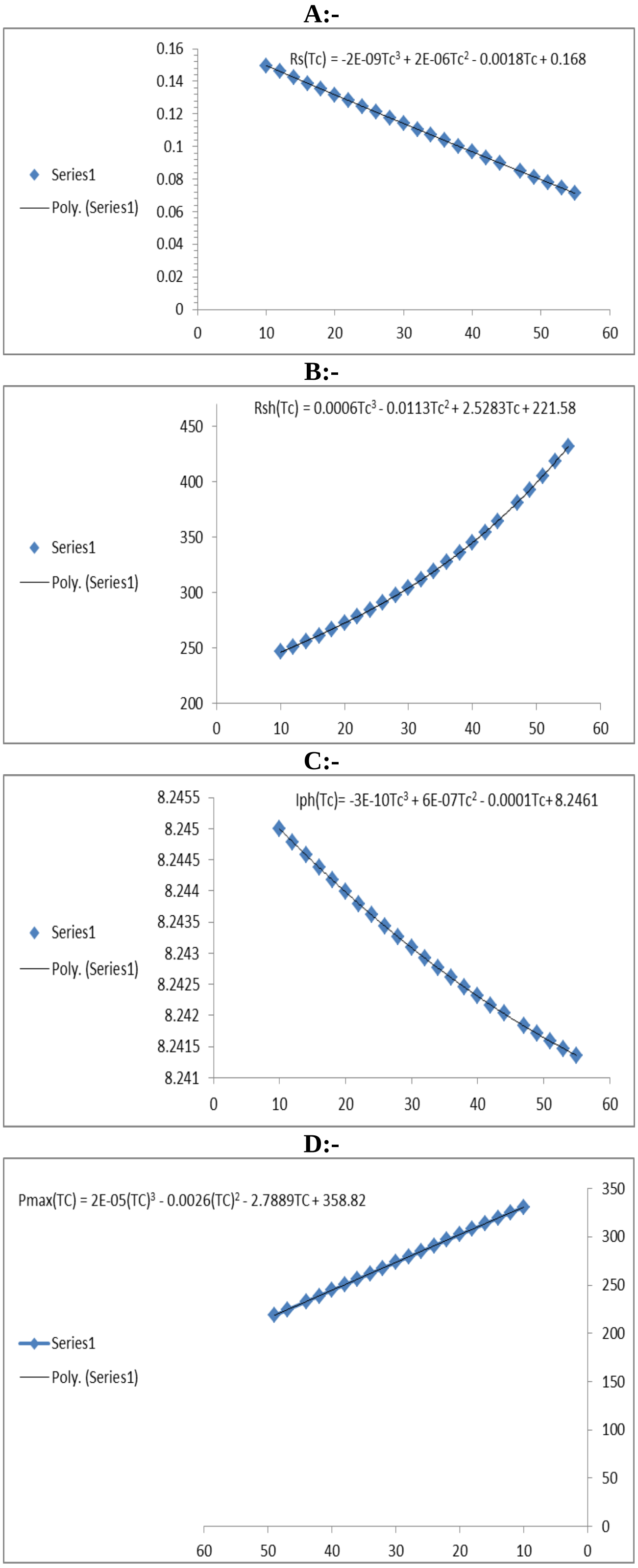

Figure4. variarion of parameters forMSMD290AS36.EU (monocrystalline) with temperature (a) Calculated $R_s(T_c)$ and polynomial regression. (b) Calculated $R_{sh}(T_c)$ and polynomial regression.(c) Calculated $I_{ph}(T_c)$ and polynomial regression.(d) Calculated maximum power $P_{max}(T_c)$

V. SIMULATION OF I-V AND P-V CURVES OF A SELECTED PV MODULES

The familiarity of current and voltage relationship of photovoltaic modules under real operating conditions is essential for the determination of their power output. Normally, the cells are mounted in modules, and multiple modules are used in arrays to get desired power output. Individual modules may have cells connected in series and parallel combinations to obtain the required current and voltage. Similarly, the array of modules may be arranged in series and parallel connections. When the cells or modules are connected in series, the voltage is additive, and when they are attached in parallel, the currents are additive [34-38]. The power output of PV modules could be predicted from the behavior of current-voltage, *I-V*, and power-voltage, *P-V*, characteristic curves.

The power as a function of voltage is given in Figure 5. The maximum power that can be obtained corresponds to the rectangle of maximum area under *I-V* curve. At the optimum power point the power is P_{mp}, the current is I_{mp}, and the voltage is V_{mp}. Ideally, the cells would always operate at the optimum power point that matches the *I-V* characteristic of the load. Hence, the load matching is essential for extracting the maximum power from the solar photovoltaic modules. Therefore, the maximum power point tractors are preferred to optimize the output power from solar PV systems.

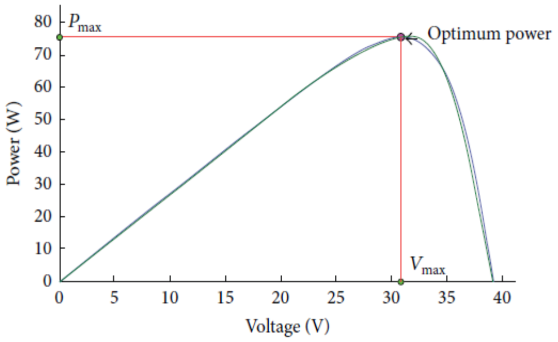

Figure 5. Typical P-V characteristics curve of a PV module.

I-V and P-V characteristic curves at various solar irradiation levels are shown in Figures 6 to 9 for the two cases. The short circuit current increases in proportion to the solar radiation while the open circuit voltage increases logarithmically with solar radiation. As long as the curved portion of the *I-V* characteristic does not intersect, the short circuit current is nearly proportional to the incident solar radiation. *I-V* characteristics curves at various temperature levels are shown in figures 10 to 13 for the two cases. The short circuit current has small effect due to variation of the temperature. Increasing temperature leads to decreasing the open circuit voltage. Figure 14 and figure 15 explain comparison between the P-V characteristics curves of the two PV module, MSP290AS-36.EU(multi_crystalline)andMSMD290AS-36. EU(mono_crystalline) at standard condition 1000 W/m^2 and 25 ^{o}C. This comparison is based on the proposed approach estimation method in this paper and Carlos de Manuel(2014),represented estimation of the parameters based on the lambert W-function[39]. There figures indicates the two method have the same power output characteristics.

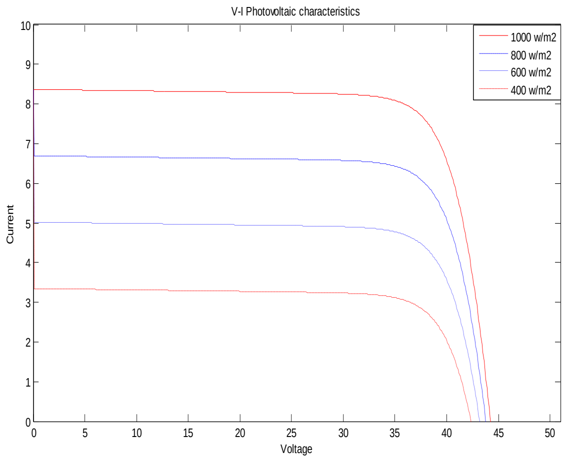

Figure 6:- variation of I-V Curve for MSP290AS-36 with radiation at constant temperature 25^{o}C

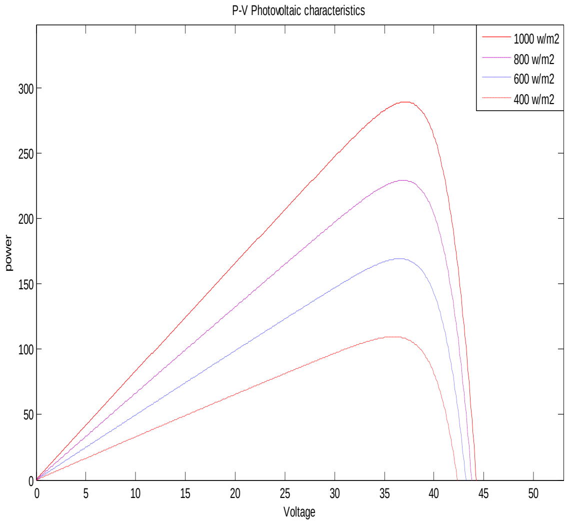

Figure 7:- variation of P-V Curve for MSP290AS-36 with radiation at constant temperature 25^{o}C

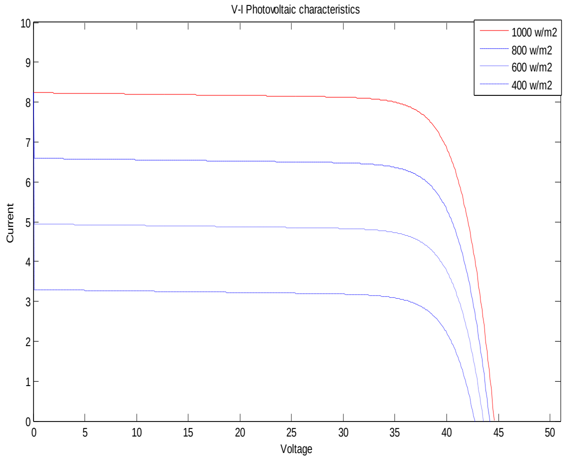

Figure 8:- variation of I-V Curve for MSMD290AS-36 with radiation at constant temperature 25^{o}C

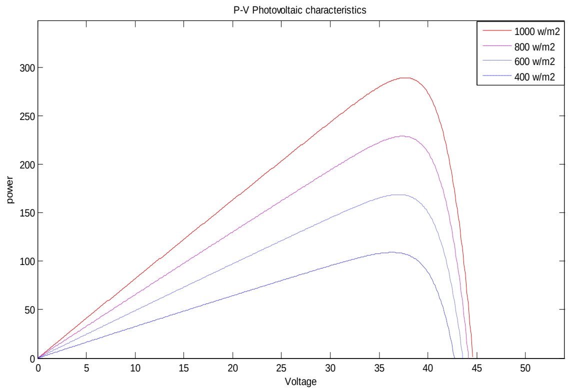

Figure 9:- variation of P-V Curve for MSMD290AS-36 with radiation at constant temperature 25°C

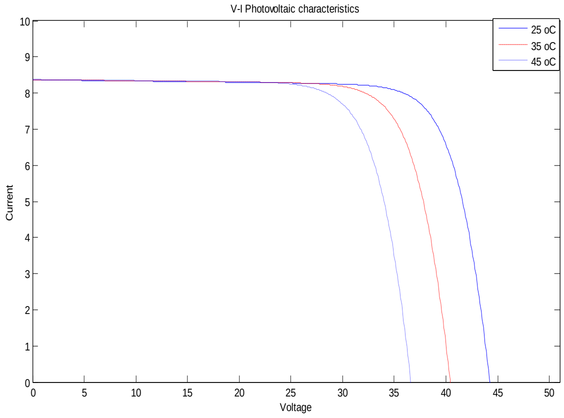

Figure 10:- variation of I-V Curve for MSP290AS-36 with temperature at constant solar radiation 1000 W/m2

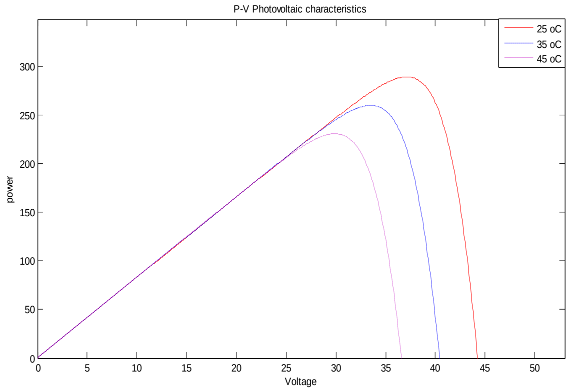

Figure 11:- variation of P-V Curve for MSP290AS-36 with temperature at constant solar radiation 1000 W/m2

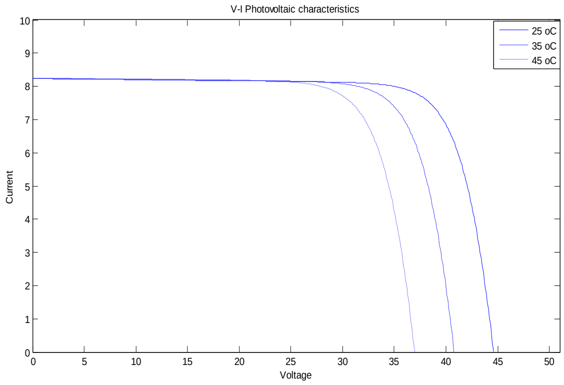

Figure 12:- variation of I-V Curve for MSMD290AS-36 with temperature at constant solar radiation 1000 W/m2

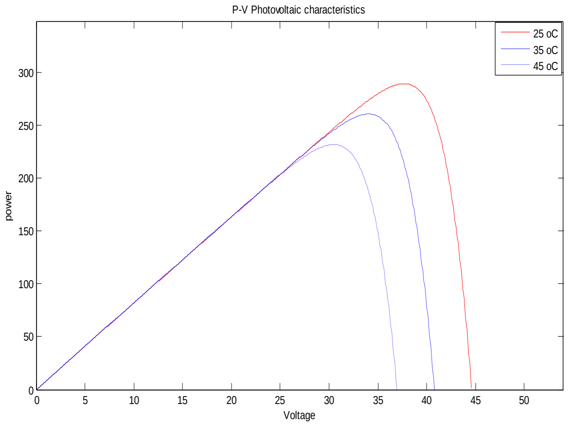

Figure 13:- variation of P-V Curve for MSMD290AS-36 with temperature at constant solar radiation 1000 W/m2

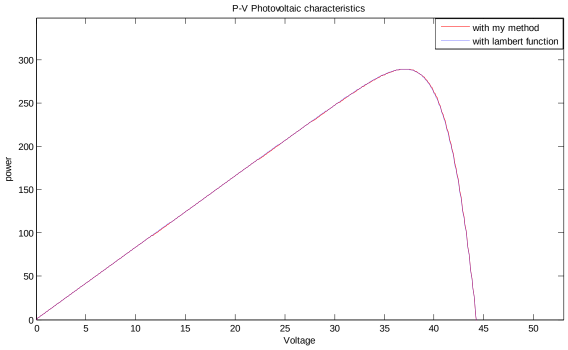

Figure 14:- variation of P-V Curve for MSP290AS-36 at STC

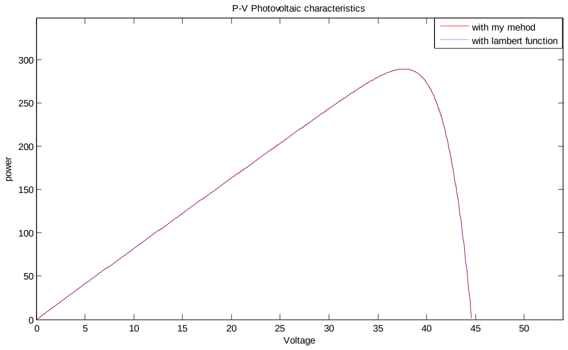

Figure 15:- variation of P-V Curve for MSP290AS-36 at STC

The *P-V* characteristics curves for various solar irradiation levels at constant temperature of 25∘C and at several temperatures with constant solar irradiance of 1000W/m2 is illustrated in Figures 7, 9, 11 and 13, respectively.

The power output of photovoltaic module by formulated model gave a 0.1688% error when compared with the rated power of PV module provided by manufacturers at standard condition 1000 W/m2 and 25 oC for MSP290AS-36.EU (multicrystalline). The power output of photovoltaic module by formulated model gave a 0.156% error when compared with the rated power of PV module provided by manufacturers at standard condition 1000 W/m^2 and 25 ^{o}C for MSMD290AS-36.EU (monocrystalline). However, at higher solar radiation and temperature values, the model simulated results were somehow deviated from the rated power of PV module.

Since, the shunt resistance (R_{sh}) was assumed to be infinity in the proposed model. It was found from the analysis that the increase of temperature and decrease of incident solar radiation levels lead to lower power output and vice versa. The power output from PV modules approaches zero, if the amount of solar radiation tends to decrease and the temperature goes up.

VI. CONCLUSIONS

In the present work a simple but accurate method to simulate the performances of a photovoltaic device for different working conditions is presented. The method is based in the analytical determination of the parameters of an equivalent circuit. Using the presented methodology it is possible to construct a realistic model of a solar panel that reproduces the experimental data provided by the manufacturer in the datasheet, including variations at different temperatures and irradiations. The method is explicit, non-iterative and straight forward; no iterations or initial values for the parameters are needed. Only data typically included in manufacturers' datasheets are required. The proposed approach explains the relation which governs the exchange in the parameters due to the variation of the cell temperature. It can be observed how parameter R_s turns negative for high temperatures (the value of parameter R_{sh} could also turn negative under some conditions). Obviously, these solutions are mathematically valid but they are not physically possible. The used model is implemented as a MATLAB® script which yields the *I-V* and *P-V* characteristics of the PV panel under variations of cell temperature and solar irradiance. The power output of photovoltaic module by formulated model gave a 0.1688% error when compared with the rated power of PV module provided by manufacturers at standard condition1000 W/m^2 and 25 ^{o}C for MSP290AS-36.EU (multicrystalline). The power output of photovoltaic module by formulated model gave a 0.156% error when compared with the rated power of PV module provided by manufacturers at standard condition 1000 W/m^2 and 25 ^{o}C for MSMD290AS-36.EU (monocrystalline). It was found that the proposed model is more practical in terms of precise estimations of photovoltaic module power output for any required location and number of variables used.

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