

## Modeling and Simulation of Egyptsat-1 Satellite System Powered by Photovoltaic Module

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**Abstract:** The paper presents a method of simulating photovoltaic module by tacking the manufacturer specified data sheet at standard test condition as inputs. A method for estimating the unknown parameters of the general single diode solar cell model using Newton's raphson method is described. The fourth parameters  $I_{ph}$ ,  $I_s$ ,  $R_s$ , and  $R_{sh}$  of the photovoltaic module are calculated with the aim of three remarkable points on the photovoltaic I-V characteristics and make  $P_{max,m} = P_{max,e}$ . The developed model allows the predication of photovoltaic module behavior with respect changes on environmental and physical parameters. The main idea of this paper is to make a computer digital model instead of real model for photovoltaic module used in Egyptsat-1 satellite, and explain the relation of  $I_{ph}$  and  $I_s$  as a function of  $R_s$  and  $R_{sh}$ .

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### 1. Introduction

Photovoltaic solar energy is a clean, renewable, energy with a long service life and high reliability. However because of its high cost and low efficiency, energy contribution is less than other energy sources. It is therefore essential to have effective and flexible models, to enable you to perform easy manipulation of certain data (for example, irradiance and temperature) investigate how to get its performance as maximum as possible. The use of these simple models provides sufficient accuracy to analyze the behavior of the solar cell and have proven to be effective in most cases [1].

The principle advantages associated with photovoltaic are that they have no moving part; they don't produce any noise; require little maintenance, low mass and work quite satisfactorily with beam or diffuse radiation posing no health or environmental hazards. Currently, solar are not very efficient with only 12-27% efficiency in their ability to convert sunlight to electrical power [2].

The modeling and simulation of photovoltaic (PV) have made a great transition and form an important part of power generation in this present age. The modeling of PV module generally involves the approximation of the non-linear I-V curve. Many researchers used circuit based approach to characterize the PV module of which the simplest model is the current source in parallel to a diode [3].

The main objective of this paper is to present a method to estimate the unknown parameters of photovoltaic module, and simulation I-V and P-V

curves under the influence of module temperature, irradiance, series resistance, and shunt resistance. The paper proceeded as follows: modeling of ideal and general photovoltaic cell is presented in section two. Modeling of general photovoltaic module is presented in section three. Modeling algorithm of iterative solution to estimate unknown parameters is presented in section four. In section five, applying the above sections on Egyptsat-1 photovoltaic module as a case study to determine the unknown parameters and show the influence of varying the module temperature, irradiance, series resistance, and shunt resistance. Conclusion is presented in section six.

### 2. Modeling of photovoltaic cell

Solar cell is basically a p-n Junction as shown in Fig.1. As sunlight strikes a solar cell, the incident energy is converted into electrical energy. Transmitted light is absorbed with in the semiconductor, by using this light energy to excite free electrons from a low energy status to an unoccupied higher energy level. When a solar cell is illuminated, excess electron-hole pairs are generated throughout the material, hence the p-n Junction is electrically shorted and current flows. During darkness, the solar cell isn't an active device; it works as diode [4-6].

Fig.2. shows the equivalent circuit of the PV cell part (b) shows the ideal PV cell part (a) shows the general model of the PV cell. The basic equation from the theory of semiconductors [7-8] that mathematically describes the I-V characteristic of the ideal PV cell is

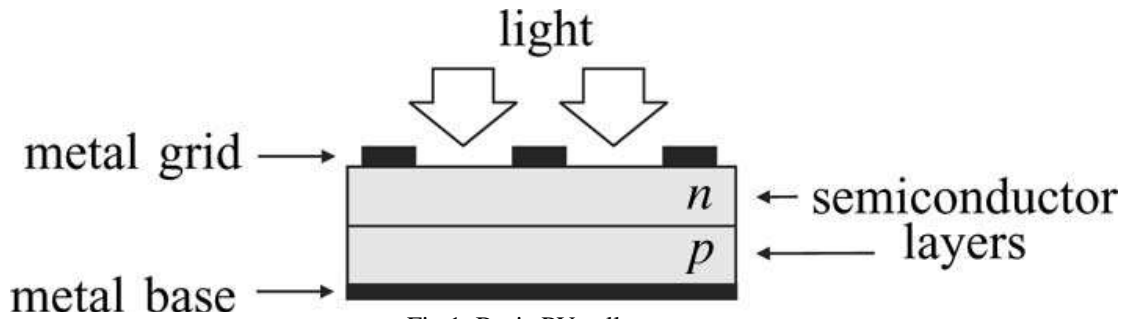


Fig.1. Basic PV cell structure

$$I = I_{ph} - I_s \left[ e^{\frac{qV}{AKT_c}} - 1 \right] \tag{1}$$

Where  $I_{ph}$  is the current generated by the incident light,  $I_s$  is the reverse saturation or leakage current of the diode,  $q$  is the electron charge ( $1.6 \times 10^{-19}$  C),  $K$  is the Boltzmann constant ( $1.38 \times 10^{-23}$  J/K),  $T_c$  (in Kelvin) is the actual temperature of the p-n junction, and  $A$  is the diode ideality factor.

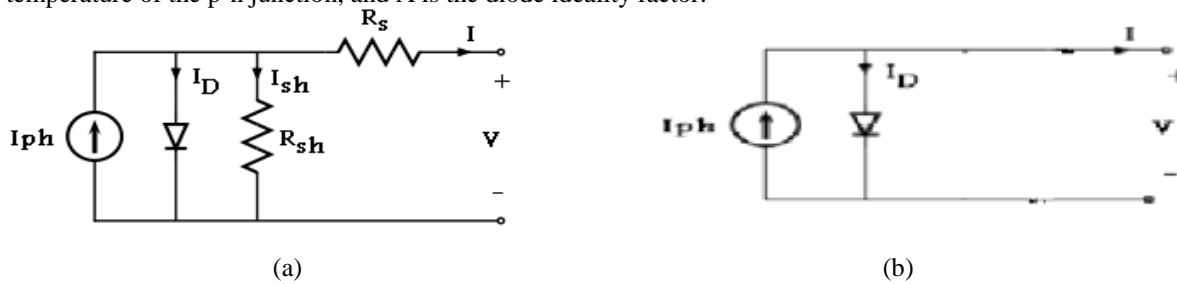


Fig.2. Solar cell models

### 3. Modeling the PV module

The basic equation (1) of the elementary PV cell does not represent the  $I-V$  characteristic of a practical PV array. Practical arrays are composed of several connected PV cells and the observation of the characteristics at the terminals of the PV array requires the inclusion of additional parameters such as the series and parallel resistance to the basic equation as shown in equation (2) [6,9-11].

$$I = I_{ph} - I_s \left[ e^{\frac{q(V+IR_s)}{AKN_sT_c}} - 1 \right] - \frac{(V + IR_s)}{R_{sh}} \tag{2}$$

Where  $N_s$  is number of cells connected in series,  $R_s$  is series resistance,  $R_{sh}$  is shunt resistance. This equation originates the  $I-V$  curve in Fig.3. where three remarkable points are highlighted: short circuit point ( $0, I_{sc}$ ), maximum power point (MPP) ( $V_{mp}, I_{mp}$ ), and open circuit point ( $V_{oc}, 0$ ).

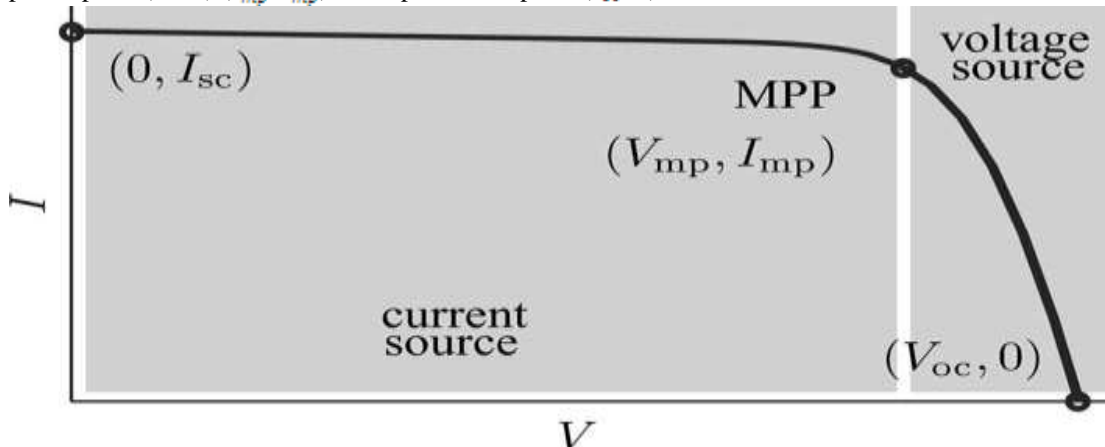


Fig.3. Characteristic  $I-V$  curve of a practical PV device and the three remarkable points

The simplicity of the single-diode model with the method for adjusting the parameters and the improvements proposed in this paper make this model perfect for power electronics designers who are looking for an easy and effective model for the simulation of PV devices with power converters. Manufacturers of PV arrays, instead of the  $I-V$  equation, provide only a few experimental data about electrical and thermal characteristics. Unfortunately, some of the parameters required for adjusting PV array models cannot be found in the manufacturer's datasheets, such as the light-generated or PV current, the series and shunt resistances, the diode ideality constant, the diode reverse saturation current, and the **bandgap** energy of the semiconductor. All PV array datasheets bring basically the following information: the nominal open-circuit voltage ( $V_{oc}$ ), the nominal short-circuit current ( $I_{sc}$ ), the voltage at the MPP ( $V_{mpp}$ ), the current at the MPP ( $I_{mpp}$ ), the open-circuit voltage/temperature coefficient ( $K_v$ ), the short circuit current/temperature coefficient ( $K_i$ ), and the maximum experimental peak output power ( $P_{max,e}$ ). This information is always provided with reference to the nominal condition or standard test conditions (STCs) of temperature and solar irradiation. Some manufacturers provide  $I-V$  curves for several irradiation and temperature conditions. These curves make easier the adjustment and the validation of the desired mathematical  $I-V$  equation. Basically, this is all the information one can get from datasheets of the PV arrays [6].

The  $R_s$  resistance is the sum of several structural resistances of the device Fig. 1 shows the structure of a PV cell.  $R_s$  Basically depends on the contact resistance of the metal base with the  $p$  semiconductor layer, the resistances of the  $p$  and  $n$  bodies, the contact resistance of the  $n$  layer with the top metal grid, and the resistance of the grid [6]. The  $R_{sh}$  resistance exists mainly due to the leakage current of the  $p-n$  junction and depends on the fabrication method of the PV cell. The value of  $R_{sh}$  is generally high and some authors neglect this resistance to simplify the model. The value of  $R_s$  is very low, and sometimes this parameter is neglected too [6].

The  $I-V$  characteristic of the PV device shown in Fig. 6 depends on the internal characteristics of the device ( $R_s, R_{sh}$ ) and on external influences such as irradiation level and temperature. The amount of incident light directly affects the generation of charge carriers, and consequently, the current generated by the device. The light-generated current ( $I_{ph}$ ) of the elementary cells, without the influence of the series and parallel resistances, is difficult to determine. Datasheets only inform the nominal short circuit current ( $I_{sc}$ ), which is the maximum current available

at the terminals of the practical device. The assumption  $I_{sc} \approx I_{ph}$  is generally used in the modeling of PV devices because in practical devices the series resistance is low and the parallel resistance is high. The light-generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation [6]:

$$I_{ph,e} = (I_{sc} + K_i(T_c - T_r)) \frac{G}{G_n} \quad (3)$$

Where  $T_c$  &  $T_r$  being the actual and reference temperature in Kelvin respectively,  $G$  ( $W/m^2$ ) is the irradiation on the module surface, and  $G_n$  ( $W/m^2$ ) is the nominal irradiation.

During darkness, the solar cell is not active and works as a diode; a p-n junction generates a current, called the diode or dark current  $I_D$  [9-11].

$$I_D = I_s \left[ \exp\left(\frac{q(V + I R_s)}{k T_c}\right) - 1 \right] \quad (4)$$

Where,  $I_s$ , is the saturation current which varies with the cell temperature according to the equation (5) [9-11].

$$I_s = I_{rs} \left[ \frac{T_c}{T_r} \right]^2 \left[ \exp\left(\frac{q E_g}{k T_r}\right) - 1 \right] \quad (5)$$

Where  $I_{rs}$  is the nominal reverse saturation current, which is obtained by evaluating (2) at the nominal open-circuit condition, with  $V = V_{oc}$ , and  $I = 0$  according to the equation (6) [9-11].

$$I_{rs} = \frac{I_{sc} - \frac{V_{oc}}{R_s}}{\left[ \exp\left(\frac{q V_{oc}}{k T_c}\right) - 1 \right]} \quad (6)$$

#### 4. Determination of unknown's parameters

Two parameters remain unknown in (2), which are  $R_s$  and  $R_{sh}$ . A few authors have proposed ways to mathematically determine these resistances. Although it may be useful to have a mathematical formula to determine these unknown parameters, any expression for  $R_s$  and  $R_{sh}$  will always rely on experimental data. Some authors propose varying  $R_s$  in an iterative process, incrementing  $R_s$  until the  $I-V$  curve visually fits the experimental data and then vary  $R_{sh}$  in the same fashion. This is a quite poor and inaccurate fitting method, mainly because  $R_s$  and  $R_{sh}$  may not be adjusted separately if a good  $I-V$  model is desired [6].

This paper proposes a method for adjusting  $R_s$  and  $R_{sh}$  based on the fact that there is an only pair  $\{R_s, R_{sh}\}$  that warranties that  $P_{max,m} = P_{max,e} = V_{mpp} I_{mpp}$  at the  $(V_{mpp}, I_{mpp})$  point of the  $I-V$  curve, i.e., the maximum power calculated by the  $I-V$  model of (2) ( $P_{max,m}$ ) is equal to the maximum experimental power from the datasheet ( $P_{max,e}$ ) at the MPP. Conventional modeling methods found in the literature take care of the  $I-V$  curve but forget that the  $P-V$  (power versus

voltage) curve must match the experimental data too. Works like [13] and [14] gave attention to the necessity of matching the power curve but with different or simplified models. For example, in [13], the series resistance of the array model is neglected. The relation between  $R_s$  and  $R_{sh}$ , the only unknowns of equation (2), may be found by making  $P_{max,m} = P_{max,e}$  and solving the resulting equation for  $R_s$ , as shown.

$$P_{max,m} = V_{mp} \left\{ I_{ph} - I_s \left[ e^{\frac{q(V_{mp} + I_{mp}R_s)}{kAT_c}} - 1 \right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \right\} = P_{max,e} \quad (7)$$

$$R_{sh} = \frac{V_{mp}(V_{mp} + R_s I_{mp})}{\left\{ V_{mp} I_{ph} - V_{mp} I_s \left( e^{\frac{q(V_{mp} + I_{mp}R_s)}{kAT_c}} \right) + V_{mp} I_s - P_{max,e} \right\}} \quad (8)$$

#### 4.1. Iterative Solution of $R_s$ and $R_{sh}$

The aim is to find the value of  $R_s$  and hence,  $R_{sh}$  that makes the peak of the mathematical  $P-V$  curve coincide with the experimental peak power at the  $(V_{mp}, I_{mp})$  point. This requires several iterations until  $P_{max,m} = P_{max,e}$ . In the iterative process,  $R_s$  must be slowly incremented starting from  $R_s = 0$ . Adjusting the  $P-V$  curve to match the experimental data requires finding the curve for several values of  $R_s$  and  $R_{sh}$ . Actually, plotting the curve is not necessary, as only the peak power value is required. Plotting the  $P-V$  and  $I-V$  curves requires solving equation (2) for  $I \in [0, I_{sc}]$  and  $V \in [0, V_{oc}]$ . Equation (2) does not have a direct solution because  $I = f(V, I)$  and

$V = f(I, V)$ . This transcendental equation must be solved by a numerical method and this imposes no difficulty. The points of  $I-V$  curve are easily obtained by numerically solving  $g(V, I) = I - f(V, I) = 0$  for a set of  $V$  values and obtaining the corresponding set of  $I$  points. Initial guesses for  $R_s$  and  $R_{sh}$  are necessary before the iterative process starts. The initial value of  $R_s$  may be zero. The initial value of  $R_{sh}$  may be given by equation (9), which is the slope of the line segment between the short-circuit and the maximum-power remarkable points. Although  $R_{sh}$  is still unknown, it surely is greater than  $R_{sh,min}$  and this is a good initial guess.

$$R_{sh,min} = \frac{V_{mp}}{I_{sc} - I_{mp}} \quad (9)$$

The values of  $R_s$  and  $R_{sh}$  are initially unknown but as the solution of the algorithm is refined along successive iterations the values of  $R_s$  and  $R_{sh}$  tend to the best solution and equation (10) becomes valid and effectively determines the light-generated current  $I_{ph}$  taking in account the influence of the series and parallel resistances of the array.

$$I_{ph} = \frac{R_{sh} + R_s}{R_{sh}} I_{ph,n} \quad (10)$$

#### 4.3 Modeling Algorithm

The simplified flowchart of the iterative modeling algorithm is illustrated in Fig.4.

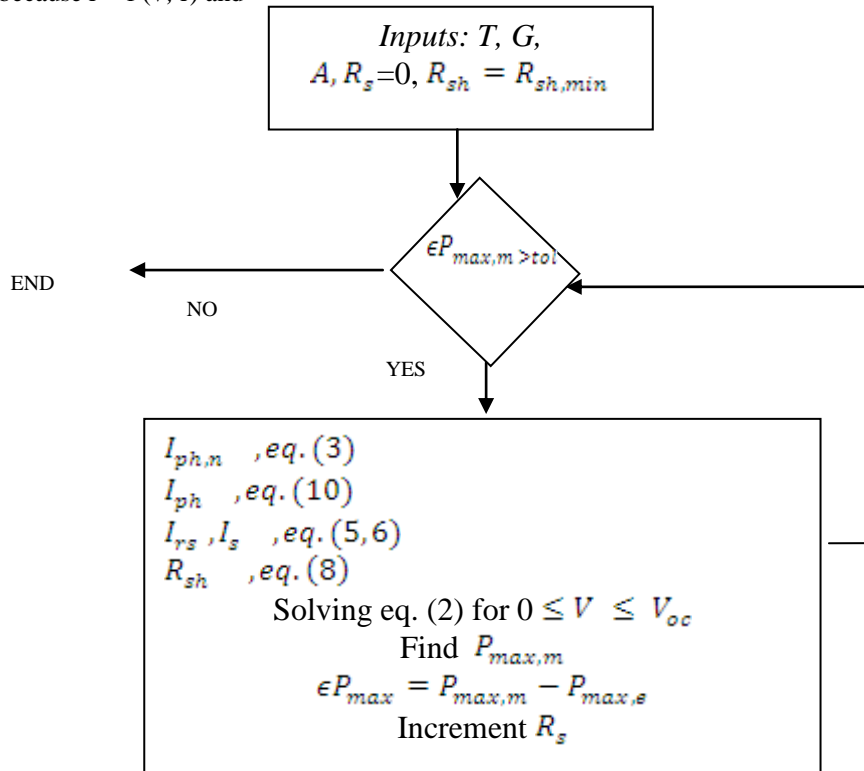


Fig.4. the modeling algorithm of estimating the unknown parameters

**5. Egyptsat-1 satellite photovoltaic module.**

The case study module consists of two parallel sections, each section consists of five parallel rows, and each row consists of 43 series cell. The model described in the above section to determine the unknown parameters to the module characteristics is applied to the module datasheet shows in table 1.1 [12].

Hence the unknown parameters are shown in Table 1.2.

Table 1.1: Electrical characteristic data of Uni - junction, GaAs, PV module

$V_{oc}$	43.532	volt
$I_{sc}$	2.56	Amp
$V_{mp}$	38.032	volt
$I_{mp}$	2.412	Amp
A	1.3	
$K_i$	0.0069	A/°c
$E_g$	1.1	ev
Area of module	0.4	m <sup>2</sup>

Table 1.2: Parameters of the adjusted model of the Uni - junction, GaAs, PV module

$I_{ph}$	2.561176
$I_s$	$1.73071 \times 10^{-13}$
$R_s$	0.294
$R_{sh}$	639.302495
A	1.3

The module output current, I, and the module output power, P, are affected by the temperature varying, irradiance effect, shunt resistor, and series resistor. This varying appears in the I-V curves and P-V curves as shown in Figs. 5-12.

**5.1 Effects of solar radiation variation**

The PV module current is strongly dependent on the solar radiation. The short circuit current decrease from 2.56 to 1.05 **amper** and the power decrease from 91.585 to 34.513 **watt**, as the solar radiation decrease from 1000 **w/m<sup>2</sup>** to 400 **w/m<sup>2</sup>**.

The model simulation result in the I-V curve and P-V curve due to change in solar radiation are shown in Fig.5. and Fig.6.respectively.

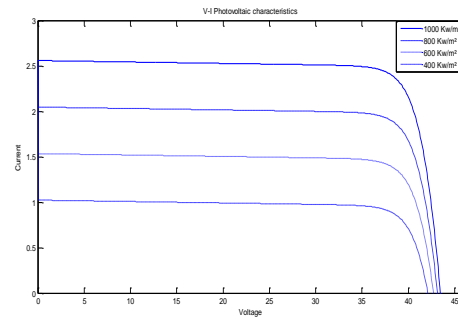


Fig.5. I-V characteristic-varying irradiance with constant temperature

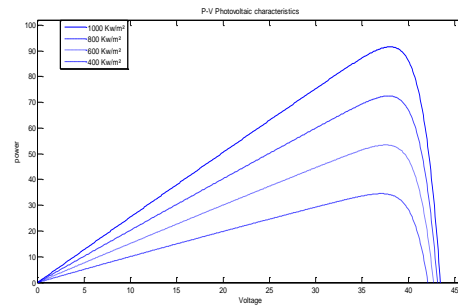


Fig.6. P-V characteristic-varying irradiance with constant temperature

**5.2 Effect of varying cell temperature**

Temperature affects the characteristic equation in two ways: directly, via  $T_c$  in the exponential term, and indirectly via its effect on  $I_s$ . While increasing  $T_c$  reduce the magnitude of the exponent in the characteristic equation, the value of  $I_s$  increases exponentially with increasing  $T_c$ . The net effect is to reduce  $V_{oc}$  linearly with increasing temperature. While the cell temperature increases from 25°C to 55 °C, the change in  $V_{oc}$  with temperature is about -0.4% /°C. The model simulation result in the I-V curve and P-V curve due to change in cell temperature are shown in Fig.7.and Fig.8.respectively.

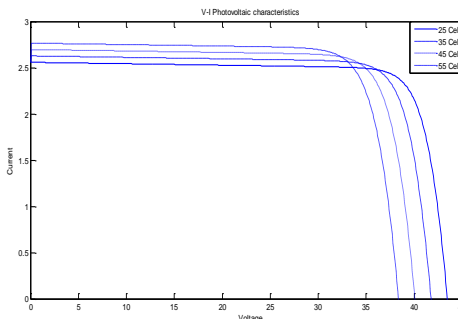


Fig.7. I-V characteristic-varying temperature with constant irradiance

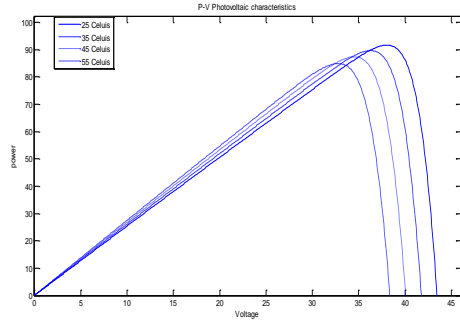


Fig.8. P-V characteristic-varying temperature with constant irradiance

**5.3 Effect of varying series resistor**

As series resistance increases, the voltage drop between the junction voltage and the terminal voltage becomes greater for the same current. The result is that the current controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal voltage and a slight reduction in  $I_{sc}$ . The series resistance of the PV cell is low, and in some cases, it can be neglected. The variation of  $R_s$  affects the slope angle of the I-V curves resulting in a deviation of the maximum power point as shown in Fig.9 and Fig.10 respectively.

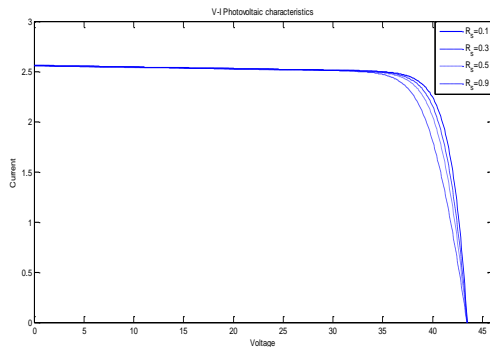


Fig.9. I-V characteristic-varying series resistance with constant irradiance & Temperature

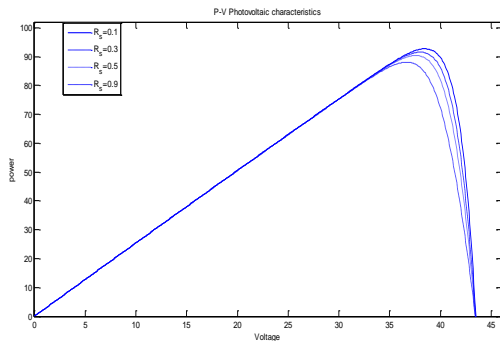


Fig.10. P-V characteristic-varying series resistance with constant irradiance & Temperature

**5.4 Effect of varying shunt resistor**

The shunt resistance of any PV cell should be large enough for higher output power and fill factor. For a low shunt resistance, the PV module output current collapses more steeply which means higher power loss and lower fill factor. The power decreases from 91.585 to 65.5101 watt, as the shunt resistance decreases from 639  $\Omega$  to 50 $\Omega$ . The model simulation result in the I-V curve and P-V curve due to change in shunt resistance shown in Fig.11 and Fig.12 respectively.

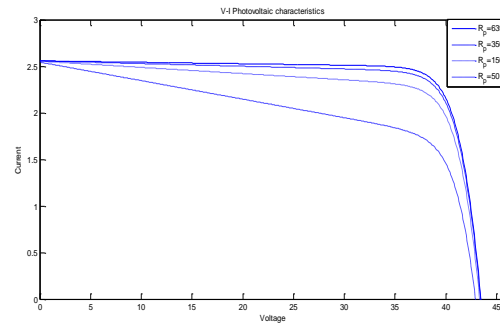


Fig.11. I-V characteristic-varying shunt resistance with constant irradiance & Temperature

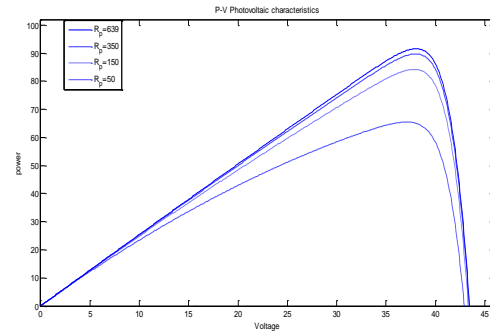


Fig.12. P-V characteristic-varying shunt resistance with constant irradiance & Temperature

**6. Conclusion**

An alternative approach to predict the I-V and P-V characteristics of the photovoltaic system using the single diode fourth parameters model is presented in this paper. This approach is based on datasheet parameters. The fourth parameters  $I_{ph}$ ,  $I_s$ ,  $R_s$ , and  $R_{sh}$  of the photovoltaic system are calculated with the aim of three remarkable points on the I-V curve and make  $P_{max,m} = P_{max,e}$ . Moreover, the assumption  $I_{ph} \approx I_{sc}$  used in most of previous works on photovoltaic modeling was replaced in this paper by a relation between  $I_{ph}$  and  $I_{sc}$  based on series and shunt resistance. Moreover, the assumption  $I_s$  depends on data sheet parameters, was replaced in this paper as a function of series and shunt resistance. The

photovoltaic system behavior under the effect of varying temperature, irradiance, series resistance, and shunt resistance is predicted.

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