



AENSI Journals

Journal of Applied Science and Agriculture

ISSN 1816-9112

Journal home page: www.aensiweb.com/JASA



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

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ARTICLE INFO

Article history:

Received 15 May 2014

Received in revised form 9 June 2014

Accepted 2 July 2014

Available online 15 September 2014

Key words:

Modeling, Simulation, Photovoltaic system, Egyptsat-1, Low Earthling Orbit satellite, Matlab Code package software

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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To Cite This Article: M.R. Taherykhani, B. Noshad, T. karymian, M.R. Taherykhani, H.R. Seriyasat, H. Zamany, Modeling and Simulation of Egyptsat-1 Satellite System Powered by Photovoltaic Module. *J. Appl. Sci. & Agric.*, 9(14): 46-54, 2014

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 (Sedra, A.S. and K.C. Smith, 200).

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 (Adedamolaomole,).

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 (Atlas, I.H., A.M. Sharaf, 2007).

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.

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 (Da Silva R.M. and J.L.M. Fernandes, 2010; Francisco, M., 2005; Huan-Liang Tsai, *et al.*, 2008).

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 (M'oller H.J., 1993; Marcelo Gradella Villalva *et al.*, 2009) that mathematically describes the $I-V$ characteristic of the ideal PV cell is

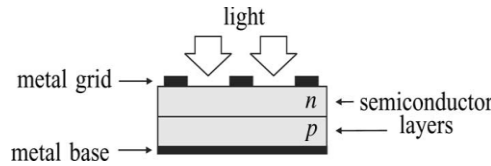


Fig. 1: Basic PV cell structure

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

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.

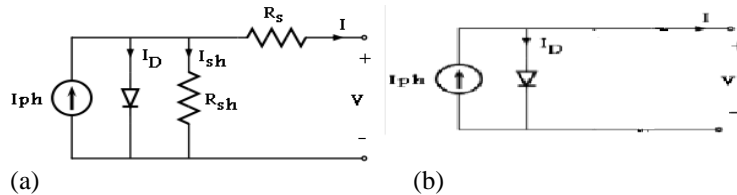


Fig. 2: Solar cell models

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) (Huan-Liang Tsai *et al.*, 2008; National Authority; Rahmani, O. and A. Taherkhani, 2014; Seryasat, O.R., *et al.*, 2014).

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

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 ($V_{oc}, 0$).

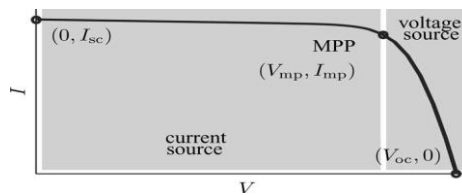


Fig. 3: Characteristic $I-V$ curve of a practical PV device and the three remarkable points

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_{mp}), the current at the MPP (I_{mp}), the open-circuit voltage/temperature coefficient (K_v), the short circuit current/temperature coefficient (K_i), and the maximum experimental peak output power ($P_{mam,e}$). 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 (Huan-Liang Tsai, *et al.*, 2008)

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 (Huan-Liang Tsai, *et al.*, 2008). 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 (Huan-Liang Tsai, *et al.*, 2008).

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 (Huan-Liang Tsai, *et al.*, 2008):

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

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 (National Authority; Rahmani, O. and A. Taherkhani, 2014; Seryasat, O.R., *et al.*, 2014).

$$I_D = I_s \left[e^{\frac{q(V+IR_s)}{AKN_s T_c}} - 1 \right] \quad (4)$$

Where, I_s , is the saturation current which varies with the cell temperature according to the equation (5) (National Authority; Rahmani, O. and A. Taherkhani, 2014; Seryasat, O.R., *et al.*, 2014).

$$I_s = I_{rs} \left[\frac{T_c}{T_r} \right]^3 \left[e^{\frac{qE_g}{AK} \left[\frac{1}{T_r} - \frac{1}{T_c} \right]} \right] \quad (5)$$

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) (National Authority; Rahmani, O. and A. Taherkhani, 2014; Seryasat, O.R., *et al.*, 2014).

$$I_{rs} = \frac{I_{ph} - \frac{V_{oc}}{R_{sh}}}{\left[e^{\frac{qV_{oc}}{AKN_s T_r}} - 1 \right]} \quad (6)$$

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 (Huan-Liang Tsai, *et al.*, 2008).

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 $P_{max,m} = P_{max,e} = V_{mp} I_{mp}$ at the (V_{mp}, I_{mp}) 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 (Rustemli, S., F. Dincer, 2011) and (Kinal Kachhiya *et al.*, 2011) gave attention to the necessity of matching the power curve but with different or simplified models. For example, in (Rustemli, S., F. Dincer, 2011), 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.

$$P_{max,m} = V_{mp} \left\{ I_{ph} \right.$$

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

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.

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

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.

$$I_{ph} = \frac{R_{sh} + R_s}{R_{sh}} I_{ph,n} \tag{10}$$

Modeling Algorithm:

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

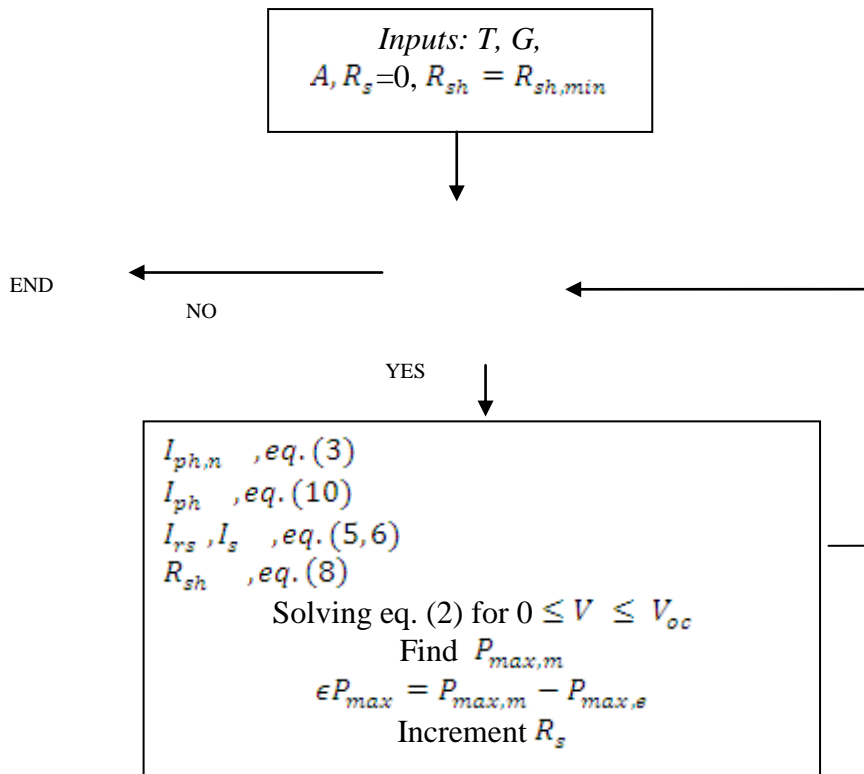


Fig. 4: the modeling algorithm of estimating the unknown parameters

Egyptosat-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 (Ramos, J.A. *et al.*, 2012).

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_j	0.0069	A/ $^{\circ}$ c
E_g	1.1	ev
Area of module	0.4	m^2

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

I_{ph}	2.561176
I_s	1.73071×10^{-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.

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^2 to 400 w/m^2 .

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.

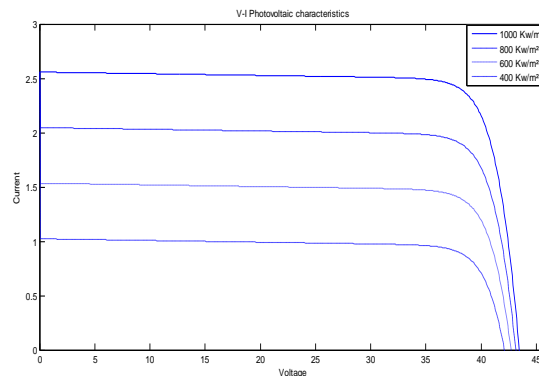


Fig.5. I-V characteristic-varying irradiance with constant temperature

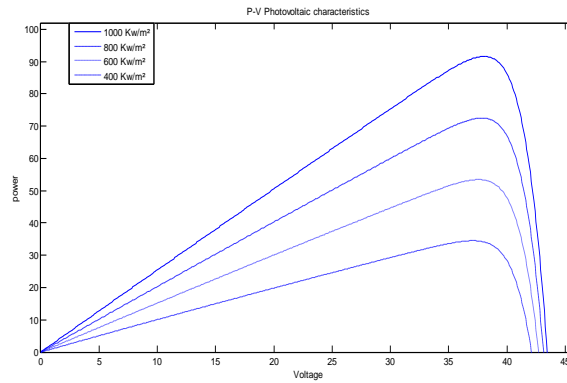


Fig. 6: P-V characteristic-varying irradiance with constant temperature

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.

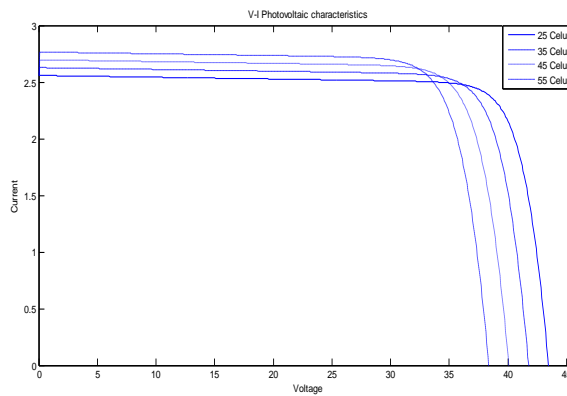


Fig. 7: I-V characteristic-varying temperature with constant irradiance

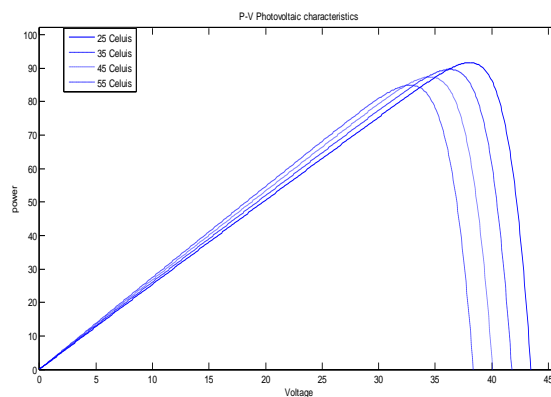


Fig. 8: P-V characteristic-varying temperature with constant irradiance

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

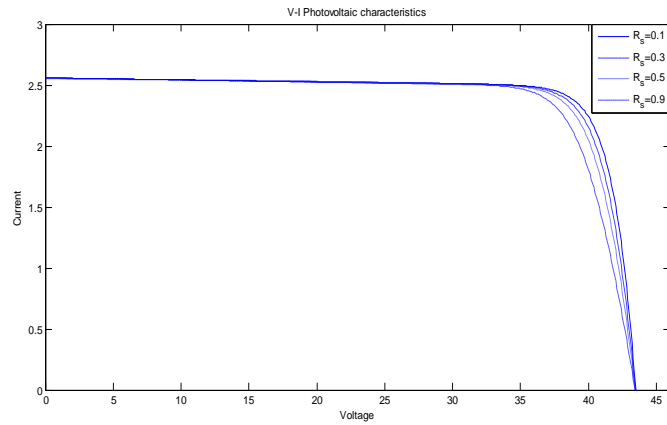


Fig. 9: I-V characteristic-varying series resistance with constant irradiance & Temperature

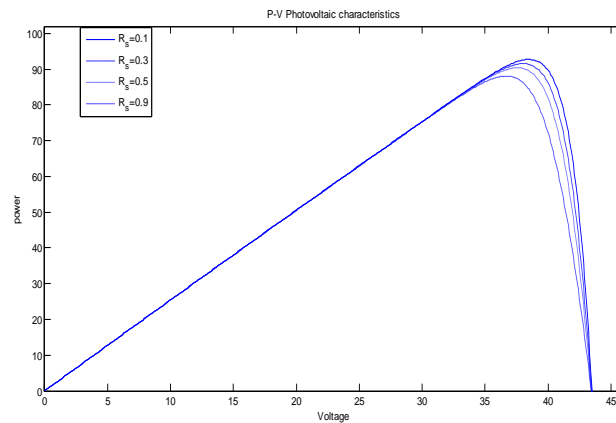


Fig. 10: P-V characteristic-varying series resistance with constant irradiance & Temperature

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 Ω to 50 Ω . 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.

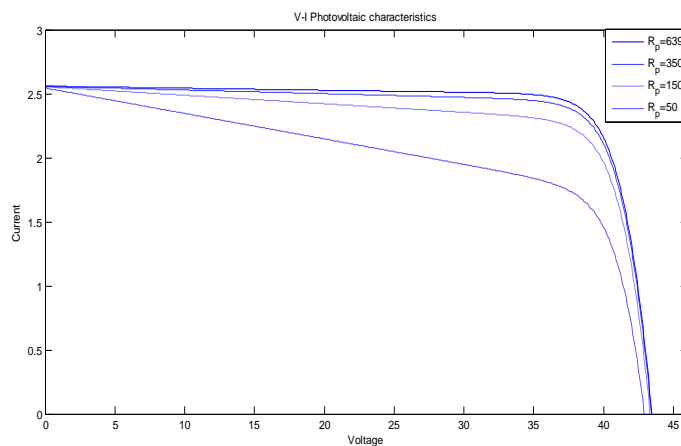


Fig. 11: I-V characteristic-varying shunt resistance with constant irradiance & Temperature

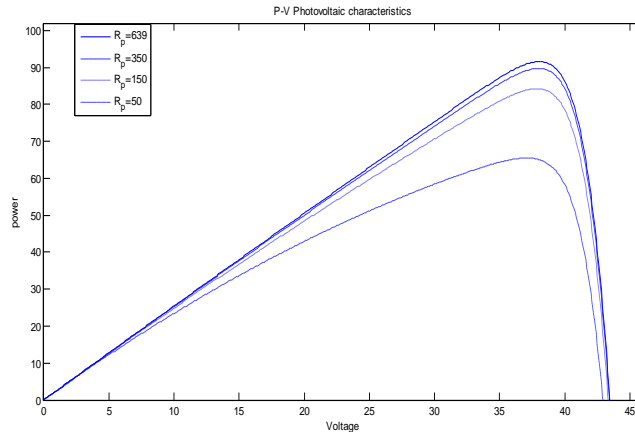


Fig. 12: P-V characteristic-varying shunt resistance with constant irradiance & Temperature

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 $P_{mam,m} = P_{mam,e}$. 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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