

A new method for accurate estimation of PV module parameters and extraction of maximum power point under varying environmental conditions

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Received: 31.12.2013

Accepted/Published Online: 07.04.2014

Final Version: 15.04.2016

Abstract: The objective of this paper is to estimate the values of five parameters (A , R_{se} , R_{sh} , I_{LG} , and I_{sat}) of a PV module more accurately and to extract the maximum power point (MPP) accurately under varying environmental conditions. Suitable new equations are proposed, by which the values of the series and shunt resistances are initialized in order to obtain good convergence speed in the Gauss–Seidel method. In this work, two new equations are proposed to find the ideality factor and shunt resistance and to obtain accurate MPP of the PV model under varying environmental conditions. The proposed PV model is validated at standard test conditions and under varying environmental conditions. Current–voltage and power–voltage characteristics of different PV modules are simulated using MATLAB. Accuracy of the proposed model is validated by comparing with the results of an adaptive neuro-fuzzy inference system and experimental data taken under varying environmental conditions.

Key words: Photovoltaic (PV) module, PV modelling, five-parameter model, maximum power point (MPP)

1. Introduction

The reserves of fossil fuels are rapidly decreasing at present due to the increased use of thermal power plants and air pollution associated with the combustion of fossil fuels is increasing. Hence, in the present scenario, there is an urgent need to speed up the research and development of renewable energy technology, especially solar energy, to meet the world energy demand. Photovoltaic (PV) systems generate green energy with no pollution and have a long life time. In the past, the energy conversion efficiency of PV modules was 10%–14% [1]. Recently, efficiency has been increased to 15%–22% in commercially available PV modules and a research laboratory reported that the efficiency of solar cells is up to 44.7% [2].

In many studies, researchers neglect either shunt resistance [3] or series resistance [4] in the four-parameter PV model. Hence, the simulated four-parameter model's $I - V$ characteristics curve does not exactly match that of the experimental $I - V$ characteristics of the PV module [3]. The five-parameter PV model considers both series resistance and shunt resistance along with light generated current, diode reverse saturation current, and ideality factor. Hence, the accuracy of the five-parameter model is found to be high and the experimental $I - V$ curve of the PV module matches the $I - V$ curve obtained from simulation results [5,6]. In the five-parameter PV model, if the value (i.e. estimated at STC) of any one of the parameters such as ideality factor, series resistance, and shunt resistance is kept constant, it reduces the accuracy of the model [7].

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The series resistance equation has been considered to find the MPP [8]. The shunt resistance equation is used to calculate the value of shunt resistance for a vertical parallel junction solar cell under constant multispectral light [9]. Here, in this work, the series resistance and shunt resistance equations are utilized to obtain initial values of R_{se} and R_{sh} respectively in the Gauss–Seidel (G-S) method. When these equations are used in the G-S method, the convergence speed of the proposed PV model improves.

The PV module’s shunt resistance, series resistance, and ideality factor change according to the environmental conditions. In this paper, two new equations are introduced for the calculation of shunt resistance and ideality factor depending upon temperature and irradiance, while finding MPP. In addition, the series resistance equation is also used for the calculation of MPP. Precise values of these three parameters are utilized for extracting the MPP more accurately. In this work, the performance of the PV module with shunt resistance variation, due to change in environmental conditions, and with constant shunt resistance is analyzed, while calculating the MPP of the PV module at all operating conditions. Here, the unknown parameters of the PV module and the MPP are evaluated by simulation using MATLAB and the results are compared with the manufacturer datasheet values. The simulated $I - V$ and $P - V$ characteristics curves of the UPV Solar U5-80 PV module are compared with the experimental curves.

This paper is organized as follows. Section 2 deals with the equation of the equivalent circuit of the PV module. Section 3 presents the extraction of PV module parameters. The effects of varying irradiance and temperature are analyzed in section 4. In section 5, the MPP is estimated. The results are discussed in section 6. Section 7 summarizes the work.

2. Equivalent circuit of the PV module

A single diode model of the PV module is shown in Figure 1. Using Kirchoff’s current law, the $I - V$ relationship of the PV module can be written as follows [10,11]:

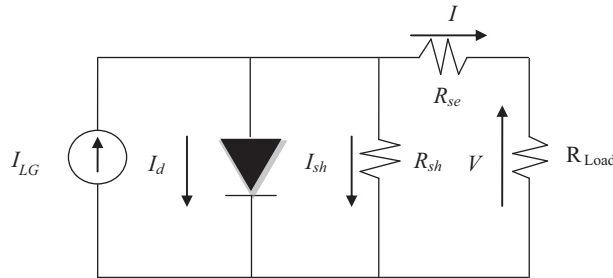


Figure 1. Equivalent circuit of single diode solar PV module.

$$I = I_{LG} - I_{sat} \left[e^{\left(\frac{V + IR_{se}}{N_s V_t} \right)} - 1 \right] - \frac{V + IR_{se}}{R_{sh}}, \tag{1}$$

where

- I – Output current at terminals in amps
- V – Output voltage at terminals in volts
- I_{LG} – Light generated current in amps
- N_s – Number of solar cells connected in series
- I_{sat} – Diode reverse saturation current in amps
- R_{se} – Series resistance of solar module in ohms

R_{sh} – Shunt resistance of solar module in ohms.

The diode thermal voltage, V_t , is expressed as

$$V_t = \frac{AkT_c}{q}, \tag{2}$$

where

A – Diode ideality factor

k – Boltzmann constant (1.3806×10^{-23} J/K)

T_c – PV module temperature (STC) in K

q – Electronic charge (1.602×10^{-19} C)

Figure 1 has five unknown parameters, namely I_{LG} , I_{sat} , A , R_{se} , and R_{sh} . In general, the aforesaid parameters are determined by numerical methods and analytical methods [12]. Using the datasheet information provided by the manufacturer of the PV module at standard test conditions (STCs), the PV module’s parameters are estimated. By using the PV module parameters obtained at STCs, the values of the five parameters and the MPP of the PV module can be estimated [6,10] at any temperature and irradiance condition.

Short circuit current I_{sc} , open circuit voltage V_{oc} , and maximum power point (V_{mpp} , I_{mpp}) are the important parameters to be noted from the manufacturer’s datasheet. Table 1 shows the values of these parameters for three different PV modules considered in this paper. These values are given at STCs, for which the irradiance (G_{stc}) is 1000 W/m^2 and the cell temperature (T_{stc}) is $25 \text{ }^\circ\text{C}$. The data sheet also provides temperature coefficients for short circuit current (k_i), open circuit voltage (k_v), and maximum power (k_p).

Table 1. Manufacturer’s datasheet values and estimated parameters values for various PV modules using MATLAB simulation at STCs.

PV module	Datasheet values					Estimated parameters				
	I_{sc} (A)	I_{mpp} (A)	V_{oc} (V)	V_{mpp} (V)	N_s	A	$R_{se}(\Omega)$	$R_{sh}(\Omega)$	I_{LG} (A)	I_{sat} (A)
KD245GX	8.91	8.23	36.9	29.80	60	1.430	0.156	623.23	8.91	4.71e-7
U5-80	5.21	4.58	21.34	17.46	36	1.606	0.009	68.10	5.21	2.79e-6
Shell SP70	4.7	4.25	21.4	16.5	36	1.553	0.324	321.22	4.70	1.56e-6

3. Extraction of PV module parameters

To estimate the five unknown parameters of the PV module from the nonlinear equation (1), five independent equations are required. The first three equations, (4), (7), and (9), are derived from Eq. (1) by applying short circuit, open circuit, and MPP conditions. The remaining two equations, (12) and (14), are derived by differentiating the values of power and current with respect to voltage [12].

3.1. Short circuit condition (SCC)

Under the short circuit condition,

$$I_{sc} = I_{LG} - I_{sat} \left[e^{\left(\frac{I_{sc} R_{se}}{N_s V_t} \right)} - 1 \right] - \frac{I_{sc} R_{se}}{R_{sh}} \tag{3}$$

After some approximation, the light generated current (I_{LG}) can be described as follows [5,11]:

$$I_{LG} = \frac{I_{sc}(R_{se} + R_{sh})}{R_{sh}} \quad (4)$$

3.2. Open circuit condition (OCC)

Under the open circuit condition,

$$0 = I_{LG} - I_{sat}e^{\left(\frac{V_{oc}}{N_s V_t}\right)} - \frac{V_{oc}}{R_{sh}} \quad (5)$$

Eq. (5) is rearranged and the reverse saturation current can be expressed as follows:

$$I_{sat} = \left(I_{LG} - \frac{V_{oc}}{R_{sh}}\right)e^{\left(\frac{-V_{oc}}{N_s V_t}\right)} \quad (6)$$

Eq. (4) is inserted into Eq. (6) and then the saturation current can be derived from the following equation [5,11]:

$$I_{sat} = \left(\frac{I_{sc}(R_{se} + R_{sh}) - V_{oc}}{R_{sh}}\right)e^{\left(\frac{-V_{oc}}{N_s V_t}\right)} \quad (7)$$

3.3. Maximum power point (MPP) condition

The MPP condition is applied in Eq. (1) and I_{mpp} can be described as follows:

$$I_{mpp} = I_{LG} - I_{sat}\left[e^{\left(\frac{V_{mpp} + I_{mpp}R_{se}}{N_s V_t}\right)} - 1\right] - \frac{V_{mpp} + I_{mpp}R_{se}}{R_{sh}} \quad (8)$$

Eqs. (4) and (7) are inserted into Eq. (8) and rearranged, by which I_{mpp} can be expressed as follows:

$$I_{mpp} = \left(\frac{I_{sc}(R_{se} + R_{sh}) - (V_{mpp} + I_{mpp}R_{se})}{R_{sh}}\right) - \left(\frac{I_{sc}(R_{se} + R_{sh}) - V_{oc}}{R_{sh}}\right)e^{\left(\frac{V_{mpp} + I_{mpp}R_{se} - V_{oc}}{N_s V_t}\right)} \quad (9)$$

At the MPP, the derivative of power with respect to voltage is zero and is expressed as [12]

$$\left.\frac{dP}{dV}\right|_{V=V_{mpp}}^{I=I_{mpp}} = 0 \quad (10)$$

Substituting $P=VI$ in Eq. (10),

$$\left.\frac{dP}{dV}\right|_{V=V_{mpp}}^{I=I_{mpp}} = \frac{d(IV)}{dV} = I + \frac{dI}{dV}V = I_{mpp} + \frac{dI_{mpp}}{dV_{mpp}}V_{mpp} \quad (11)$$

From Eqs. (11) and (9), dP/dV can be expressed as follows:

$$\left.\frac{dP}{dV}\right|_{V=V_{mpp}}^{I=I_{mpp}} = 0 = I_{mpp} + \frac{V_{mpp}\left\{\frac{-1}{R_{sh}} - \left(\frac{I_{sc}(R_{se} + R_{sh}) - V_{oc}}{R_{sh}}\right)e^{\left(\frac{V_{mpp} + I_{mpp}R_{se} - V_{oc}}{N_s V_t}\right)}\right\}}{\left\{1 + \frac{R_{se}}{N_s V_t}\left(\frac{I_{sc}(R_{se} + R_{sh}) - V_{oc}}{R_{sh}}\right)e^{\left(\frac{V_{mpp} + I_{mpp}R_{se} - V_{oc}}{N_s V_t}\right)} + \frac{R_{se}}{R_{sh}}\right\}} \quad (12)$$

Eq. (14) can be derived using $I - V$ characteristics of the PV module. The derivative of the current with respect to voltage at the short circuit condition is mainly determined by the shunt resistance R_{sh} [12].

$$\left. \frac{dI}{dV} \right|_{V=0}^{I=I_{sc}} = \frac{-1}{R_{sh}} \tag{13}$$

From Eq. (13), dI/dV can be expressed as

$$\left. \frac{dI}{dV} \right|_{V=0}^{I=I_{sc}} = \frac{-1}{R_{sh}} = \frac{\left\{ \frac{-1}{R_{sh}} - \frac{(I_{sc}(R_{se}+R_{sh})-V_{oc})e^{\left(\frac{I_{sc}R_{se}-V_{oc}}{N_s V_t}\right)}}{R_{sh}} \right\}}{\left\{ 1 + \frac{R_{se}}{N_s V_t} \frac{(I_{sc}(R_{se}+R_{sh})-V_{oc})e^{\left(\frac{I_{sc}R_{se}-V_{oc}}{N_s V_t}\right)}}{R_{sh}} + \frac{R_{se}}{R_{sh}} \right\}} \tag{14}$$

3.4. Calculation of initial values

To select the initial value for R_{se} and R_{sh} , Eqs. (15) and (16) are considered in [8,9]. Because of high sensitivity, the numerical methods may fail to converge due to improper selection of the initial value of the PV module parameters [6].

$$R_{se_initial} = \frac{V_{oc}}{I_{sc}} - \frac{V_{mpp}}{I_{mpp}} \tag{15}$$

$$R_{sh_initial} = \frac{V_{mpp}}{I_{sc} - I_{mpp}} \tag{16}$$

Eqs. (9), (12), and (14) are rearranged to determine the values of V_t , R_{se} , and R_{sh} , which are given by Eqs. (17), (18), and (19), respectively.

$$V_t = \frac{V_{mpp} + I_{mpp}R_{se} - V_{oc}}{N_s \ln\left(\frac{I_{sc}(R_{se}+R_{sh})-V_{oc}}{(I_{sc}-I_{mpp})(R_{se}+R_{sh})-V_{mpp}}\right)} \tag{17}$$

$$R_{se} = \frac{V_{oc} - V_{mpp} + N_s V_t S}{I_{mpp}}, \tag{18}$$

where $S = \ln\left(\frac{N_s V_t (I_{mpp}(R_{se}+R_{sh})-V_{mpp})}{I_{sc} V_{mpp} (R_{se}+R_{sh}) + I_{mpp} R_{se} (V_{oc} - I_{sc} R_{se} - I_{sc} R_{sh}) - V_{mpp} V_{oc}}\right)$

$$R_{sh} = \frac{N_s V_t (R_{se} + R_{sh}) + R_{sc} (I_{sc} (R_{se} + R_{sh}) - V_{oc}) e^{\left(\frac{I_{sc} R_{se} - V_{oc}}{N_s V_t}\right)}}{N_s V_t + (I_{sc} (R_{se} + R_{sh}) - V_{oc}) e^{\left(\frac{I_{sc} R_{se} - V_{oc}}{N_s V_t}\right)}} \tag{19}$$

The PV module parameters I_{LG} , I_{sat} , A , R_{se} , and R_{sh} can be obtained using Eqs. (4), (7), (17), (18), and (19). First, the transcendental equations (17), (18), and (19) are solved by the G-S method and the values of A , R_{se} , and R_{sh} are obtained. The remaining parameters I_{LG} and I_{sat} are obtained from Eqs. (4) and (7) using the values of A , R_{se} , and R_{sh} . For solving the transcendental equations by the G-S method, Eqs. (17), (18), and (19) are expressed in the form of Eq. (20) [10].

$$X_i^k = f(X_i^{k-1}), \tag{20}$$

where X is the unknown variable and k is the k th iteration. The unknown variable can be solved by using Eq. (20). Estimated values of different parameters of different PV modules using the G-S method are shown in Table 1.

The flowchart for evaluation of the five parameters of the PV module is shown in Figure 2. In Figure 2, $e1$, $e2$, and $e3$ represent the errors in A , R_{se} , and R_{sh} in the two consecutive iterations, respectively, and their value is taken as 1×10^{-6} [13].

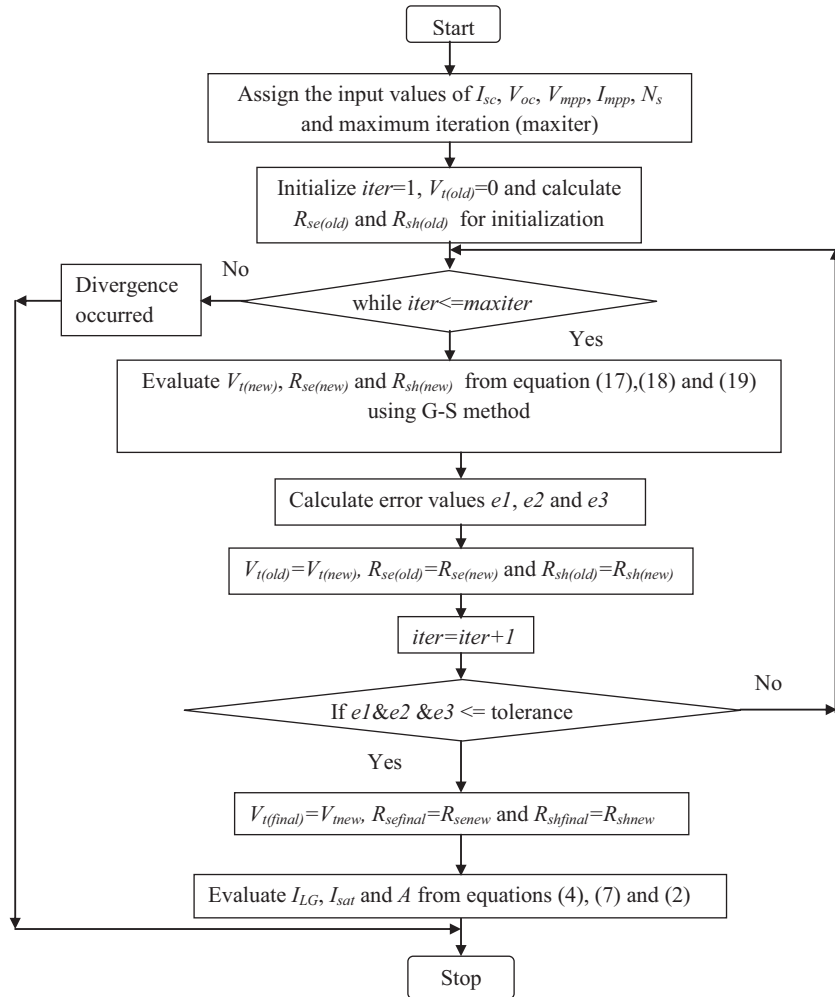


Figure 2. Flowchart to estimate the PV module parameters using the G-S method.

4. Effect of varying irradiance and temperature

The light generated current and short circuit current are directly proportional to irradiance and also depend on temperature as given in Eqs. (21) and (22) [10,14].

$$I_{LG(G)} = I_{LG(stc)} \frac{G}{G_{stc}} \tag{21}$$

$$I_{sc(G)} = I_{sc(stc)} \frac{G}{G_{stc}}, \tag{22}$$

where G_{stc} – irradiance at STC (W/m^2)

G – irradiance under given operating condition (W/m^2).

The open circuit voltage equation can be described as the function of irradiance as given by Eq. (23) [10].

$$V_{oc(G)} = N_s V_t \ln\left(\frac{I_{LG(G)} R_{sh} - V_{oc(G)}}{I_{sat} R_{sh}}\right) \quad (23)$$

The transcendental equation (23) is solved by the G-S method.

The short circuit current and open circuit voltage can be evaluated for given operating temperature as given by Eqs. (24) and (25) [15].

$$I_{sc(T)} = I_{sc(stc)} + K_i(T_c - T_{stc}) \quad (24)$$

$$V_{oc(T)} = V_{oc(stc)} + K_v(T_c - T_{stc}), \quad (25)$$

where T_{stc} – cell temperature at STC, K.

The light generated current can be determined as a function of temperature using Eq. (4) and is given by Eq. (26).

$$I_{LG(T)} \approx \frac{I_{sc(T)}(R_{se} + R_{sh})}{R_{sh}} \quad (26)$$

The short circuit current, open circuit voltage, and light generated current can be estimated at any temperature and irradiance using Eqs. (27), (28), and (29) [16–18].

$$I_{LG(GT)} = (I_{LG(stc)} + K_i(T_c - T_{stc})) \frac{G}{G_{stc}} \quad (27)$$

$$I_{sc(GT)} = (I_{sc(stc)} + K_i(T_c - T_{stc})) \frac{G}{G_{stc}} \quad (28)$$

$$V_{oc(GT)} = V_{oc(G)} + K_v(T_c - T_{stc}) \quad (29)$$

The thermal voltage V_t is directly proportional to PV panel cell temperature and is given by Eq. (30) [19].

$$V_{t(T)} = V_{t(stc)} \frac{T_c}{T_{stc}} \quad (30)$$

The diode reverse saturation current, which is a function of irradiance and temperature, can be calculated by Eq. (31) and which is obtained from Eqs. (7) and (30) [18,20].

$$I_{sat(GT)} = \left(\frac{I_{sc(T)}(R_{se} + R_{sh}) - V_{oc(GT)}}{R_{sh}}\right) e^{\left(\frac{-V_{oc(GT)}}{N_s V_{t(T)}}\right)} \quad (31)$$

5. Estimation of maximum power point

The proper initial value of V_{mpp} and I_{mpp} should be chosen to estimate the accurate MPP by using well known values of V_{oc} and I_{sc} under given operating conditions [21,22]. Under varying irradiance and temperature, $V_{t(GT)}$, $R_{se(GT)}$, and $R_{sh(GT)}$ are obtained by using the estimated parameters of the PV module such as I_{LG} , I_{sat} , A , R_{se} , and R_{sh} at STCs.

In general, the PV module parameters change considerably due to various environmental conditions. As a consequence, for accurate modelling of a PV module, the values of all five parameters are evaluated at different environmental conditions [23]. The open circuit voltage of the PV panel is decreased when the panel temperature is increased and vice versa [24]. The thermal voltage is indirectly proportional to open circuit voltage and this concept is used to form the new equation (32).

$$V_{t(GT)} = V_{t(stc)} \frac{V_{oc(stc)}}{V_{oc(GT)}} \tag{32}$$

The series resistance has a direct relationship with the variation in light generated current under varying operating conditions and is expressed in the form of Eq. (33) [10].

$$R_{se(GT)} = R_{se(stc)} \frac{I_{LG(GT)}}{I_{LG(stc)}} \tag{33}$$

The value of shunt resistance is considered a constant in [10] but the value of shunt resistance of the PV module is indirectly proportional to the short circuit current under varying operating conditions [12]. In this paper, a new equation (34) is introduced for the shunt resistance variation with respect to temperature and irradiance and is expressed as

$$R_{sh(GT)} = R_{sh(stc)} \frac{I_{sc(stc)}}{I_{sc(GT)}} \tag{34}$$

In order to find MPP, the maximum voltage (V_{mpp}) is found by rearranging Eq. (9) as a function of temperature and irradiance and is given by Eq. (35).

$$V_{mpp} = V_{oc(GT)} - I_{mpp}R_{se(GT)} + N_s V_{t(GT)}U, \tag{35}$$

where $U = \ln\left\{\frac{[I_{sc(GT)} - I_{mpp}](R_{se(GT)} + R_{sh(GT)}) - V_{mpp}}{I_{sc(GT)}(R_{se(GT)} + R_{sh(GT)}) - V_{oc(GT)}}\right\}$

The maximum current (I_{mpp}) can be extracted by reforming Eq. (12) as a function of temperature and irradiance and is given by Eq. (36).

$$I_{mpp} = \left\{ \frac{[V_{mpp}Q / (N_s V_{t(GT)} R_{sh(GT)})] + [V_{mpp} / R_{sh(GT)}]}{1 + [QR_{se(GT)} / N_s V_{t(GT)} R_{sh(GT)}] + [R_{se(GT)} / R_{sh(GT)}]} \right\}, \tag{36}$$

where $Q = [I_{sc(GT)}(R_{se(GT)} + R_{sh(GT)}) - V_{oc(GT)}] \exp\left\{\frac{V_{mpp} + I_{mpp}R_{se(GT)} - V_{oc(GT)}}{N_s V_{t(GT)}}\right\}$

Eqs. (35) and (36) are solved by the successive under relaxation (SUR) method. The general formula used in the SUR method is expressed in the form of Eq. (37) [10]:

$$X_i^k = WX_i^k + (1 - W)f(X_i^{k-1}), \tag{37}$$

where W – weighting factor.

The weighting factor, W , is assigned a value between 0 and 1 for the SUR technique. The selection of an appropriate value for W is frequently by trial and error and it is highly problem specified. If the value of the weighting factor is not chosen properly, divergence may occur. In the G-S and SUR methods, an error threshold value of 1×10^{-6} is used, which ensures that the parameters have converged to their final values [13].

Eqs. (32), (33), and (34) are substituted into Eqs. (35) and (36) to estimate the precise value of PV module parameters at the MPP. The flowchart for finding the MPP in different irradiance and temperature

conditions is illustrated in Figure 3. In Figure 3, $e1$, $e2$, and $e3$ represent the errors in $V_{t(GT)}$, $R_{se(GT)}$, and $R_{sh(GT)}$ in the two consecutive iterations, respectively.

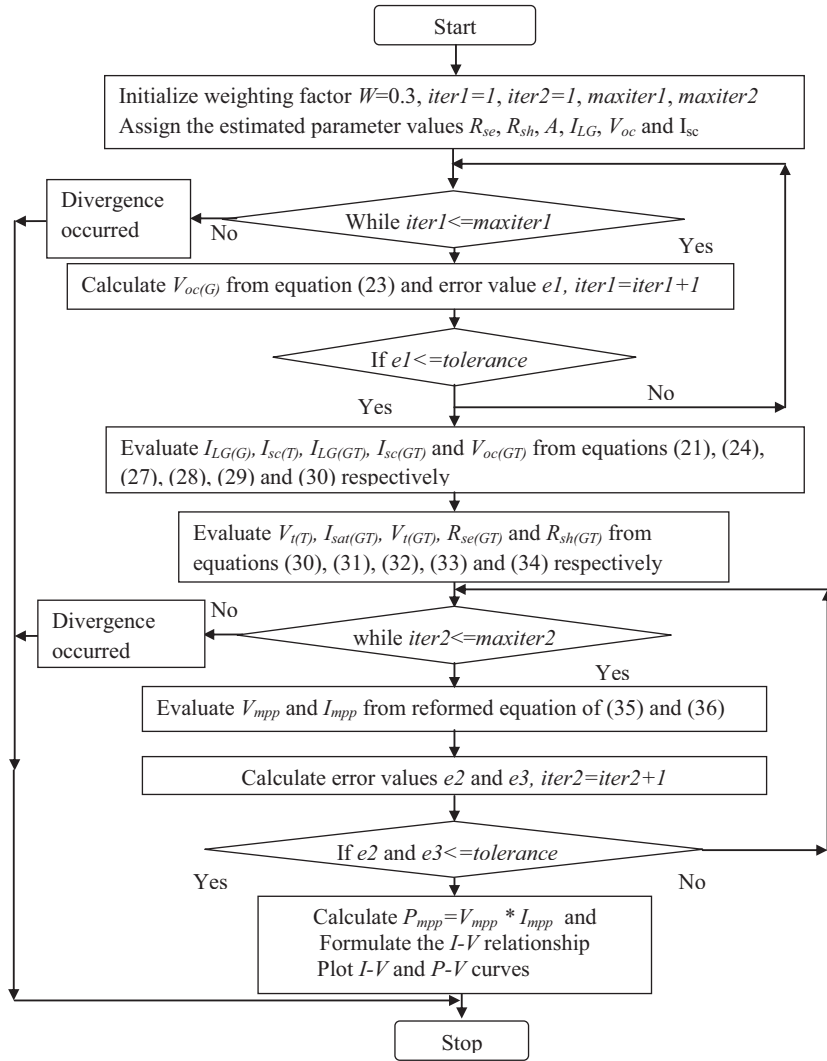


Figure 3. Flowchart to evaluate the MPP using the SUR method.

6. Results and discussion

6.1. Simulation results

In Table 2, the KD245GX PV module is considered to validate the proposed PV model for different temperature values (30 °C, 50 °C, 70 °C) with constant irradiance (1000 W/m²) and different irradiance values (1100 W/m², 800 W/m², 600 W/m²) with constant temperature (25 °C). A MATLAB m-file program is developed to evaluate the five unknown parameters of the PV module at the STCs by using the G-S method and the MPP by the SUR method, and also to obtain the $I - V$ and $P - V$ characteristics curves of the PV module. The five unknown parameters of the KD245GX PV module and MPP are estimated at the aforesaid conditions and are listed in Table 2. It is found from Table 2 that at constant irradiation if the PV module temperature increases (more than STCs temperature), the values of R_{se} , A , and I_{sat} increase by significant amounts but the

value of I_{LG} increases slightly. Simultaneously, the value of R_{sh} decreases slightly when there is an increase in temperature. As a result, the PV module output power decreases at the MPP.

Table 2. Estimated PV module parameters' values under varying irradiance and temperature in simulation.

PV Module Parameters	G (W/m ²)	T_c (°C)	A	R_{se} (Ω)	R_{sh} (Ω)	I_{LG} (A)	I_{sat} (A)	V_{mpp} (V)	I_{mpp} (A)	P_{mpp} (W)
KD245GX	1000	30	1.432	0.157	621.37	8.94	8.39e-7	29.11	8.23	239.61
	1000	50	1.450	0.159	614.02	9.05	7.04e-06	26.38	8.21	216.64
	1000	70	1.483	0.160	606.84	9.15	4.62e-05	23.68	8.16	193.14
	1100	25	1.422	0.172	566.58	9.80	4.28e-07	29.78	9.05	269.55
	800	25	1.449	0.125	779.04	7.13	5.89e-07	29.69	6.58	195.47
	600	25	1.475	0.094	1038.7	5.35	7.89e-07	29.34	4.93	144.72
Shell SP70	1000	25	1.553	0.324	321.22	4.70	1.56e-6	16.51	4.25	70.16
	800	25	1.577	0.259	401.53	3.76	1.57e-6	16.59	3.41	56.52
	600	25	1.609	0.195	535.37	2.82	1.58e-6	16.49	2.55	42.11
	400	25	1.657	0.130	803.06	1.88	1.60e-6	16.12	1.70	27.35
	200	25	1.748	0.065	1606.1	0.94	1.65e-6	15.18	0.84	12.77

In Figure 4, the $I - V$ and $P - V$ curves show the effect of rise in temperature. At constant irradiation, the PV module's V_{oc} reduces by 1.8%, 9.01%, and 16.22%, and I_{sc} increases by 0.3%, 1.5%, and 2.7%, when the temperature is 5 °C, 25 °C, and 45 °C more than the STCs temperature, respectively. Figure 4 clearly demonstrates that if the PV module temperature increases, V_{oc} decreases but I_{sc} increases slightly. This indicates that the open circuit voltage strongly depends on PV module temperature compared to the short circuit current. Due to the drop in V_{oc} , the output power at MPP is reduced by 2.27%, 11.64%, and 21.23%, respectively, for the aforesaid temperature conditions.

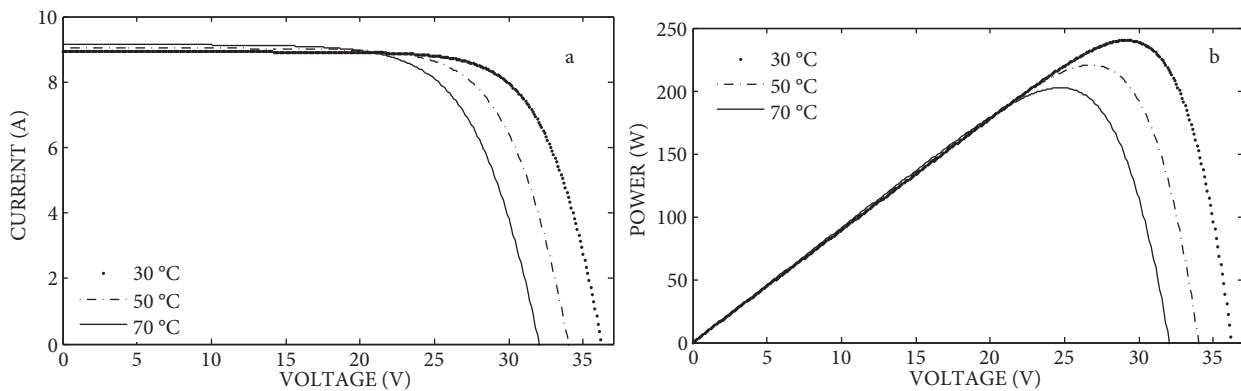


Figure 4. (a) Simulated $I - V$ curves, (b) $P - V$ curves of the KD245GX solar module at $G = 1 \text{ KW/m}^2$ and different temperatures.

From Table 2, at high irradiation condition, the PV module light generated current is larger, which increases the power losses at series resistance (R_{se}) and vice versa. When the temperature is kept constant and irradiation is reduced, the values of A and I_{sat} increase slightly; R_{se} and R_{sh} decrease and increase

respectively by large amounts. Due to the decrease in the value of R_{se} , the loss in it is reduced. Due to the increase in the value of R_{sh} , the power loss in R_{sh} is reduced because of the decrease in the leakage current in the shunt resistance. As a result, the PV module output power is slightly enhanced at the output terminal. Table 2 also indicates that, if the irradiation decreases, the I_{LG} decreases and the output power decreases and vice versa.

Figure 5 illustrates the PV module $I - V$ and $P - V$ curves that occurred due to the variation in irradiation. When the irradiation is 1100 W/m^2 , the values of I_{sc} and P_{mpp} increase by 9.99% and 9.91%, respectively, but the value of V_{oc} slightly increases by 0.57% while comparing their values at STC irradiation. While the irradiation levels are 800 W/m^2 and 600 W/m^2 , the corresponding value of I_{sc} decreases by 19.98% and 39.96%, respectively. The values of P_{mpp} also decrease by 20.3% and 40.99%, respectively. At the same time, the value of V_{oc} decreases by 1.38% and 3.12%, respectively. The obtained results show that the change in the values of I_{sc} and P_{mpp} is nearly same according to the irradiation variation.

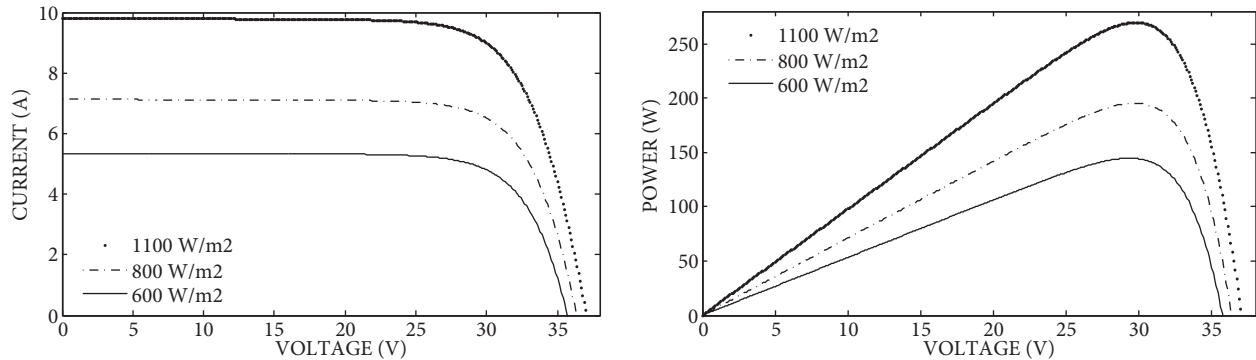


Figure 5. (a) Simulated $I - V$ curves, (b) $P - V$ curves of the KD245GX solar module at $T_c = 25 \text{ }^\circ\text{C}$ and different irradiation levels.

From Table 2, at low irradiance levels such as 800 and 600 W/m^2 at $25 \text{ }^\circ\text{C}$, the corresponding calculated value of R_{sh} increases to $779.04 \text{ } \Omega$ and $1038.7 \text{ } \Omega$, respectively. The values of R_{se} , R_{sh} , and A vary according to the environmental conditions. This leads to the actual power being obtained from the PV module. If the R_{sh} value is considered constant with varying ideality factor and varying series resistance under different environmental conditions, it leads to deviation in the PV module output power.

Under varying environmental conditions, the five unknown parameters of the Shell SP70 PV module are evaluated and I_{mpp} , V_{mpp} , and P_{mpp} are extracted. They are shown in Table 2. Using the same PV module under the same operating conditions, the maximum power obtained using the ANFIS model [11] is 69.56 W , 55.86 W , 41.63 W , 27.15 W , and 12.74 W , respectively. When this result is compared with the proposed PV model, maximum power exhibits excellent agreement. Thus, the results of the proposed model show good accuracy. Moreover, the proposed PV model does not require training data as ANFIS.

6.2. Experimental validation

A set of experimental data is observed to validate the proposed model of the PV module under different environmental conditions. The experimental setup, which uses a UPV Solar U5-80 PV module, is shown in Figure 6. Table 3 shows the observed values of V_{oc} , I_{sc} , V_{mpp} , and I_{mpp} of the UPV Solar U5-80 PV module at different temperature and irradiance conditions. The observed values are used to draw the $I - V$ curves and $P - V$ curves for the same panel as shown in Figure 7.



Figure 6. (a) Experimental setup of U5-80 PV module, (b) solar panel, (c) pyranometer.

Table 3. Experimental data observed from the U5-80 PV module.

Parameter	G (W/m^2)	T_c ($^{\circ}C$)	V_{oc} (V)	I_{sc} (A)	V_{mpp} (V)	I_{mpp} (A)	P_{mpp} (W)
PV module	351	35.7	18.61	1.82	15.20	1.55	23.56
UPV Solar U5-80	426	42	18.64	2.15	14.98	1.88	28.16
	568	44	19.06	2.88	15.08	2.56	38.60

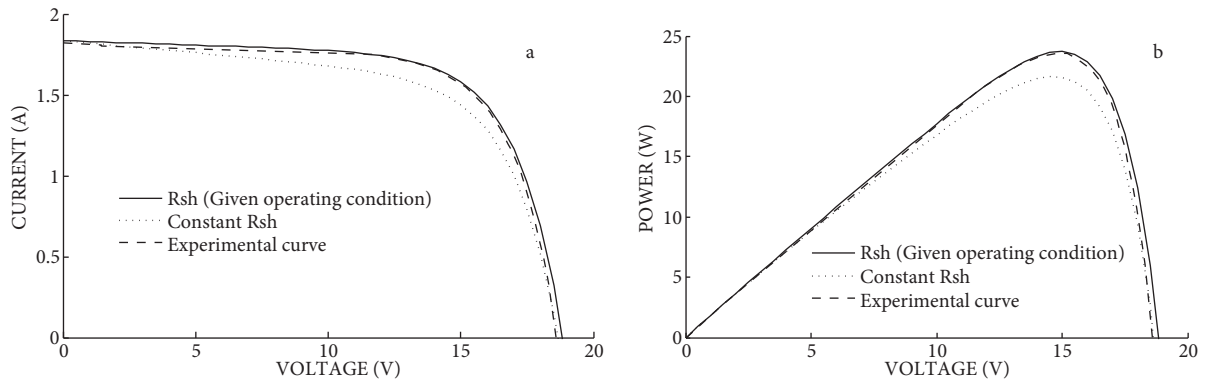


Figure 7. (a) Simulated and experimental $I - V$ curves, (b) $P - V$ curves for U5-80 PV module at $G = 351 W/m^2$ and $T_c = 35.7 ^{\circ}C$ for constant R_{sh} and varying R_{sh} case.

When R_{sh} value is high, leakage current in the shunt resistance is low and hence the output power is high. At low irradiation levels, only with a high value of R_{sh} , it is possible to accurately estimate the output power. Hence, R_{sh} is considered to be a variable that increases whenever irradiation decreases. In Table 4, the PV module power is estimated with varying R_{sh} and constant R_{sh} ($R_{sh} = 68.10 \Omega$; estimated at STCs) conditions. In the varying R_{sh} case, the power deviation is insignificant at the MPP between the power (ΔP_{mpp1}) obtained from the model and experimental data. However, at constant R_{sh} , power deviation (ΔP_{mpp2}) is high. It is shown in Table 4.

Table 4. Parameters computed and data obtained from simulation for the U5-80 PV module.

PV module Parameters	G (W/m ²)	T_c (°C)	Experimental observed power @MPP	Varying R_{sh} (given operating condition)			Constant R_{sh} ($R_{sh} = 68.10 \Omega$)	
			P_{mpp} (W)	R_{sh} (Ω)	P_{mpp1} (W)	ΔP_{mpp1} (%)	P_{mpp2} (W)	ΔP_{mpp2} (%)
UPV Solar U5-80	351	35.7	23.56	193.54	23.70	0.59	21.84	7.30
	426	42	28.16	159.54	28.56	1.42	26.94	4.33
	568	44	38.60	119.37	39.08	1.24	37.81	2.05

From Figure 7, it is found that the experimental and simulated $I-V$ and $P-V$ characteristics curves have good agreement when the shunt resistance varies according to the environmental conditions. More deviation in MPP takes place when the PV module shunt resistance is considered constant. Therefore, the proposed PV module model is more accurate.

7. Conclusion

In this paper, the G-S method is used to estimate the five unknown parameters of the PV module at STCs. Here, good convergence is achieved in the G-S method during simulation, due to the selection of appropriate initial values from the series and shunt resistance equations. The SUR method is used to extract the MPP at different environmental conditions by considering the varying nature of shunt resistance, series resistance, and ideality factor. In particular, through the proposed equations of shunt resistance and ideality factor of the PV model, accurate MPP is obtained. For a wide range of operating conditions, the MPP and the five unknown parameters of the PV module are estimated. The MPP obtained from the simulation results of the proposed PV model is found to be much closer to the experimental data and this shows the accuracy of the proposed model. Further, when the proposed PV model is compared with the ANFIS model, the proposed PV model ensures accurate results.

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