

Accurate modeling and maximum power point detection of photovoltaic module using a few collected data

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Abstract

This paper presents an algorithm for modeling and Maximum Power Point (MPP) detection of a Photo-Voltaic (PV) module. This algorithm requires less information to get an accurate model and MPP. Open circuit voltage (V_{OC}) and short circuit current (I_{SC}) of the PV module are required as inputs data. Both of them can be sampled from a reference PV Panel. A PV model and MPP are estimated via Newton-Raphson (NR) method. Fractional V_{OC} and I_{SC} method and simplified method are used for detecting the starting values of MPP and model parameters of a PV panel respectively. Then, the NR method is applied to calculate the accurate values of MPP and model parameters of it. Determination of MPP enables the PV system to deliver maximum available power. Verification of this algorithm is accomplished through building it in MATLAB. Then, it is tested for different manufacturer modules at different operating conditions.

Keywords: MPP; PV model, Accurate model; Newton-Raphson.

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1. Introduction

PV systems are the most important renewable energy conversion systems due to a continuously reduction in their energy production cost (Kannan et al., 2006; Emmott et al., 2011; Bazilian et al., 2013). Also, they have the ability to product electrical energy during less time. So, the installed capacity of PV systems is increasing continuously (Masson et al., 2013). Estimation of a PV model is important in the fabrication, designing and performance prediction of the PV systems. Many methods are used for this purpose such as (Elshatter et al., 1997; Arab et al., 2004; De Soto et al., 2006; Carrero et al., 2007; Mellit et al., 2007; Celik and Acikgoz, 2007; Villalva et al., 2009). Conventional algorithms are investigated in (Carrero et al., 2007; Villalva et al., 2009; Celik and Acikgoz, 2007; Arab et al., 2004; De Soto et al., 2006). Also the intelligent algorithms are proposed in (Elshatter et al., 1997; Mellit et al., 2007). All of these models need to measure illumination and temperature to give good accuracy model.

Determination of MPP enables the PV system to deliver maximum available power. So, there are many investigations are proposed for this purpose such as (Abdelsalam et al., 2011; Jain and Agarwal, 2007; Kok Soon et al., 2013; Kamarzaman and Tan, 2014; Sera et al., 2013; Chun and Kwasinski, 2011; Huynh et al., 2013; Hohm and Ropp, 2003; Sher et al., 2015; Salam et al., 2013; Bai et al., 2014; Ishibashi et al., 2008; Chegaar et al., 2003; Faranda and Leva, 2008; López-Lapeña et al., 2010; Khezzar et al., 2009; Simjee and Chou, 2008; Dondi et al., 2008; Bai et al., 2014; Walker, 2001; Ma et al., 2013; Roman et al., 2006; Bahgat et al., 2005; El-Sayed and Leeb, 2014; Enslin et al., 1997; Noguchi et al., 2002). The simplest methods (open circuit voltage method and short circuit method are presented) in (Enslin et al., 1997; Noguchi et al., 2002) which are easy in implementation, but these methods have less accuracy. Many studies have been carried out via Perturb and Observe (P&O) algorithm and its modification such as those given in (Abdelsalam et al., 2011; Jain and Agarwal, 2007). P&O algorithm failed due to rapidly-varying in the solar radiation, also it may take more time for convergence process because it depends on initial guess. Incremental-Conductance (IC) method is proposed for MPP estimation (Kok Soon et al., 2013). Although IC MPPT is better than the (P&O)

(Ramani et al., 2017) but its response is poor in the steady-state operation. Although, many improvements are proposed on the (P&O) and IC (Huynh et al., 2013; Hohm and Ropp, 2003; Sher et al., 2015), still there is a bad oscillatory behavior. The MPP estimation process can be carried out by using Soft Computing (SC) (Salam et al., 2013). The most common SC-MPP algorithms are the Artificial Neural Network (ANN) and Fuzzy Logic (FL) (Bahgat et al., 2005; El-Sayed and Leeb, 2014). Soft computing algorithms are more efficient than IC and P&O, but they need large data for training and periodic tuning. In Walker, (2001), MATLAB-PV modeling and MPP estimation has been presented. But, it requires insolation and temperature, for detecting V and I vectors. Ref. (Ma et al., 2013) presented an MPP DEM which works with the variety of atmospheric conditions. This method gives acceptable speed and accuracy, but it gives approximate MPP and also, temperature and solar radiation are required as input data.

In this paper, an algorithm is proposed to achieve two objectives simultaneously. These are the estimation of an accurate model and MPP of a PV module. The proposed algorithm uses V_{OC} and I_{SC} only as input data. Fractional V_{OC} and I_{SC} method and simplified method are used for detecting the starting values of MPP and the model parameters of a PV panel respectively. These values are near from the desired. So, the obtained solution via NR method is converged quickly. Verification of this algorithm is accomplished through building it in MATLAB. Then, it is tested for different manufacturer modules at different operating conditions.

2. Problem Description

The most common equivalent circuit of the PV cell is represented as shown in Fig. 1

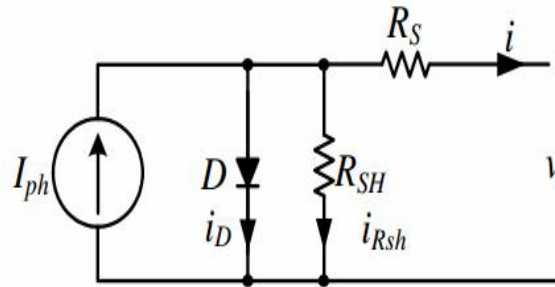


Fig. 1 Equivalent circuit of a photovoltaic cell using the single exponential module

The V-I characteristic of a PV panel based on the single exponential model is:

$$I = I_{ph} - I_o (e^{x_1 = I_{ph}} - 1) - \frac{V + IR_s}{R_{sh}} = f_i \tag{1}$$

or

$$V = I_{ph}R_{sh} - I_oR_{sh} (e^{\frac{V+IR_s}{N_sV_t}} - 1) - IR_{sh} - IR_s = f_v \tag{2}$$

Equation (1) can be written as.

$$I = x_1 - x_2 (e^{x_4 V + I x_5} - 1) - x_3 (V + \frac{I x_5}{x_4}) = f_i \tag{3}$$

Where

$$x_1 = I_{ph}, x_2 = I_o, x_3 = \frac{1}{R_{sh}}, x_4 = \frac{1}{N_s V_t}, x_5 = R_s x_4$$

In order to calculate the PV model parameters (x_1 : x_5) and detect Maximum Power Point ($x_6 = I_m$; $x_7 = V_m$) of a PV module, the current and the voltage at key operational point (the short-circuit point, the open-circuit point, and the maximum power point) are used as follow:

At short-circuit point, $V = 0, I = I_{sc}$:

$$f_1 = I_{sc} - f_i(I = I_{sc}, V = 0) = I_{sc} - x_1 + x_2 (e^{I_{sc} x_5} - 1) + x_3 (\frac{I_{sc} x_5}{x_4}) = 0 \tag{4}$$

from the slope of the I-V curve at the short circuit current point (Chegaar et al., 2003)

$$f_2 = x_5 + \frac{\partial f_i}{\partial V_i} | (I = I_{sc}, V = 0) = 0 \tag{5}$$

At open circuit point, $V = V_o, I = 0$:

$$f_3 = 0 - f_i(I = 0, V = V_{OC}) = -x_1 + x_2(e^{x_4 V_{OC}} - 1) - x_3(V_{OC}) = 0 \tag{6}$$

from the slope of the I-V curve at the open circuit point (Sera et al., 2013)

$$f_4 = \frac{x_5}{x_4} + \frac{\partial f_v}{\partial I} | (I = 0, V = V_{OC} = 0) = 0 \tag{7}$$

At maximum power point MPP, $x_6 = I_m, x_7 = V_m$

$$f_5 = I_m - f_i(I = I_m, V = V_m) = x_1 - x_2(e^{x_4 V_m + I_m x_5} - 1) - x_3(V_m + \frac{I_m x_5}{x_4}) = 0 \tag{8}$$

Where

$$P = f_i V \tag{9}$$

An additional equation can be derived using the fact that is on the P-V characteristic of the panel, at the MPP, the derivative of power is zero.

$$f_6 = \frac{\partial P}{\partial I} | (I = x_6, V = x_7) = 0 \tag{10}$$

$$f_7 = \frac{\partial P}{\partial V} | (I = x_6, V = x_7) = 0 \tag{11}$$

Equations (4-11) can be expressed in the compact form as follow:

$$f(x, u) = 0 \tag{12}$$

Where

$$x = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7] \tag{13}$$

$$f = [f_1 \quad f_2 \quad f_3 \quad f_4 \quad f_5 \quad f_6 \quad f_7] \tag{14}$$

$$u = [I_{sc} \quad V_{OC}] \tag{15}$$

3. Choosing Starting Values for Newton-Raphson Computation of MPP and PV Model Parameters

The Newton-Raphson- method requires appropriate initial guesses. This may cause the final convergence may not be guaranteed or may delay the MPP execution process. We have suggested the following method for getting optimal starting points for Newton-Raphson

3.1 Choosing Starting Values of MPP

Under any given environmental condition, the current at MPP (I_m) has approximately a linear relation with short-circuit current (I_{sc}) as expressed in the below equation

$$I_m \propto I_{sc} \tag{16}$$

$$\therefore I_m = K_{SC} I_{sc} \tag{17}$$

where k is the constant of proportionality. Value of k is unique for different PV modules. Typically, it varies from 0.72 to 0.92. Since it is an approximation, it does not track the real MPP. However, the tracking speed is fast with a reasonable efficiency up to 90% (Faranda and Leva, 2008). The FOCV method exploits the nearly linear relationship between a PV module's open-circuit voltage (VOC) and its voltage at the MPP (V_{mp}) under varying irradiance and temperature levels (López-Lapeña et al., 2010). The FOCV technique exploits the nearly linear relationship between the V_{mp} of a solar cell and its VOC as

$$V_m \propto V_{OC} \tag{18}$$

$$\tag{19}$$

$$\therefore V_m = K_{OC} V_{OC} \tag{20}$$

To include the effects of the environment, e.g. temperature and irradiance on the values of (Isc, Voc) (Khezzer, 2009).

$$I_{sc} = \frac{G}{G_{ref}} I_{sc-ref} + K_i \Delta T \approx \frac{G}{G_{ref}} I_{sc-ref} \quad (21)$$

$$V_{OC} = V_{OC-ref} + K_v \Delta T + V_t \ln\left(\frac{G}{G_{ref}}\right) \quad (22)$$

$$\therefore \frac{G}{G_{ref}} \approx \frac{I_{sc}}{I_{sc-ref}} \quad (23)$$

$$\therefore \Delta T = \frac{\Delta V_{OC} - V_t \ln\left(\frac{I_{sc}}{I_{sc-ref}}\right)}{K_v} \quad (24)$$

From quations (18-24), we can deduce that

$$x_6^{(0)} = I_m = \frac{I_{sc}}{I_{sc-ref}} I_{m-ref} + K_i \frac{\Delta V_{OC} - V_t \ln\left(\frac{I_{sc}}{I_{sc-ref}}\right)}{K_v} \quad (25)$$

$$x_7^{(0)} = V_m = V_{m-ref} + K_m \frac{\Delta V_{OC} - V_t \ln\left(\frac{I_{sc}}{I_{sc-ref}}\right)}{K_v} + V_t \ln\left(\frac{I_{sc}}{I_{sc-ref}}\right) \quad (26)$$

Where

Ki, Kv, Km Temperature coefficient of the short-circuit current - open-circuit voltage and maximum voltage respectively.

3.2 Choosing Starting Values of PV Parameters

The initial estimation of PV parameters is critical because a bad starting point can compromise the convergence of the Newton-Raphson's method. The initial values of these parameters are estimated by using the simplified method (Khezzer et al., 2009). In this method some of the approximations are applied as (Isc=Iph, and Rsh=), after simplification of equations (4-10) we obtain:

$$x_1^{(0)} = I_{sc} \quad (27)$$

$$x_4^{(0)} = \frac{\frac{I_{sc}}{I_{sc} - x_6^{(0)}} + \ln\left(1 - \frac{x_6^{(0)}}{I_{sc}}\right)}{2x_7^{(0)} - V_{OC}} \quad (28)$$

$$x_2^{(0)} = x_1^{(0)} e^{-x_4^{(0)} V_{OC}} \quad (29)$$

$$x_5^{(0)} = \frac{V_{OC} - x_7^{(0)} + \ln\left(1 - \frac{x_6^{(0)}}{I_{sc}}\right)}{x_6^{(0)}} \quad (30)$$

$$x_3^{(0)} = \frac{x_1^{(0)} - x_2^{(0)} e^{x_5^{(0)} I_{sc}}}{V_{OC}} \quad (31)$$

4. The Proposed Procedure for Accurate Modeling and Maximum Power Point Detection of Photovoltaic Module using a Few Collected Data

The determination of unknown parameters $x_1:x_7$ (MPP and model parameter) of the PV module at various operation conditions is described in the following steps:-

Step 1: detection of the inputs of the algorithm (open circuit and short circuit only) which can be measured by using different methods (Sher et al., 2015; Simjee and Chou, 2008; Dondi et al., 2008; Bai et al., 2014).

Step 2: estimate of the initial MPP and model parameters ($x^{(0)}$) by using equations 22-28.

Step 3: The elements of the resulting Jacobian matrix (J) are obtained by differentiating equation (12) as follows:

$$J\Delta x = \Delta f(x, u) \tag{32}$$

Where

$$J_{ij} = \frac{\partial f_i}{\partial x_j} \tag{33}$$

$$\Delta x = J^{-1}\Delta f(x, u) \tag{34}$$

The correction values can be calculated as follows:

$$\Delta f^{it} = 0 - f^{it-1} \tag{35}$$

$$x^{it} = x^{it-1} + \Delta x \tag{36}$$

Step 4: The process of iteration (equations 33-36) are repeated until the values of these corrections are minimized.

5. Results and Discussion

The previous section describes the proposed algorithm construction of a PV panel model. This algorithm has been implemented in MATLAB, in order to verify it at the different values open circuit and short circuit which are varied corresponding to temperature and irradiance conditions. The proposed model was tested using different manufacturer data sheets as in Table1.

Table 1. Datasheet for KC200GT solar module sand SP75 solar module at 25 C, AM1.5, and 1000 W/m2

Parameter	KC200GT solar Module (Shell, 2018)	SP75 solar Module (KC200GT, 2018)
Pm	200 W	75 W
Vm	26.3 V	17 V
Im	7.61 A	4.4 A
Voc	32.9 V	21.7 V
Isc	8.21 A	4.8 A
kV	- 0.123V/oC	- 76 mV/oC
Ki	+ 3.18 mA/oC	+ 2 mA/oC
number of cells (ns)	54	36

The determination of unknown parameters $x_1:x_7$ (MPP and model parameter) of the PV module at various operating conditions is described in pervious section The proposed model is tested for different manufacturer modules under different condition. These parameters are used to plot a voltage-curent characteristic of a PV moduel according to eq 3. The calculated data have been compared to the characteristics and values provided by the product data-sheet.

It can be seen from Figs. (2-7) that the calculated V-I curves based on the proposed PV model are in very good agreement with the data-sheet values for SP75 (mono-crystalline silicon) solar module and KC200GT (multicrystal).

To evaluate the accuracy of the proposed model, the corresponding normalized root mean square error percentage [nRMSE(%)] is calculated at different conditions and calculated by

$$nRMS\% = \frac{\sqrt{\frac{1}{N} \sum_1^N (E_i - T_i)^2}}{\sqrt{\frac{1}{N} \sum_1^N (T_i)^2}} * 100 \tag{36}$$

where E_i is the estimated value, and T_i is true values obtained from data sheet of KC200GT. Table 2 gives the evaluated nRMSE(%). As it can be seen from this Table 2, the proposed model has presented the good accuracy under different conditions. In addition, it is seen that the accuracy of the estimated values of maximum power are in good tolerance.

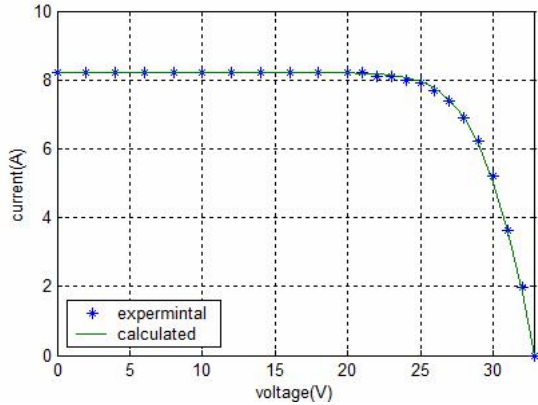


Fig. 2 V-I Char. of the KC200GT model (multicrystal) at $V_o=32.9$, $I_{sc}=8.21$, $G=1000$, $T=25$

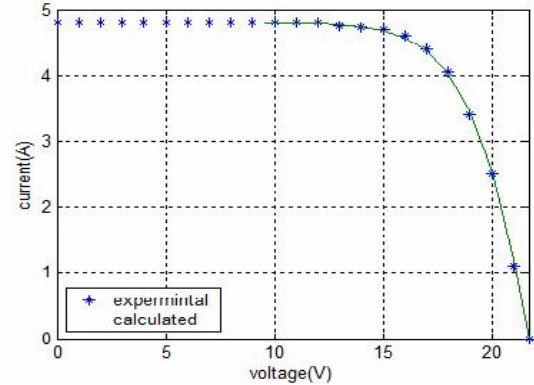


Fig. 5 V-I Char. of the shell SP75 model (monocrystalline silicon) at $V_o=21.7$, $I_{sc}= 4.8$, $G=1000$, $T=25$

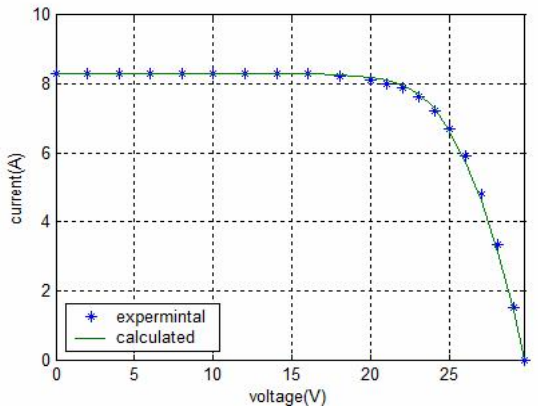


Fig. 3 V-I Char. of the KC200GT model (multicrystal) at $V_o=29.75$, $I_{sc}=8.29$, $G=1000$, $T=50$

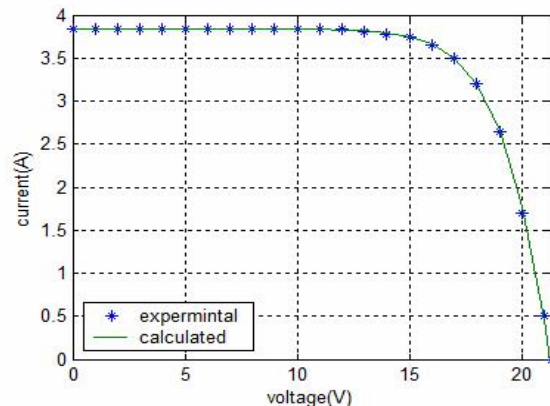


Fig. 6 V-I Char. of the shell SP75 model (monocrystalline silicon) at $V_o=21.3$ $I_{sc}= 3.84$, $G=800$, $T=25$

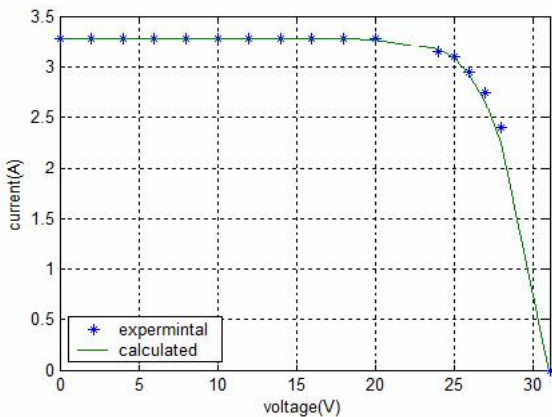


Fig. 4 V-I Char. of the KC200GT model (multicrystal) at $V_o=1.1$, $I_{sc}=3.28$, $G=400$, $T=25$

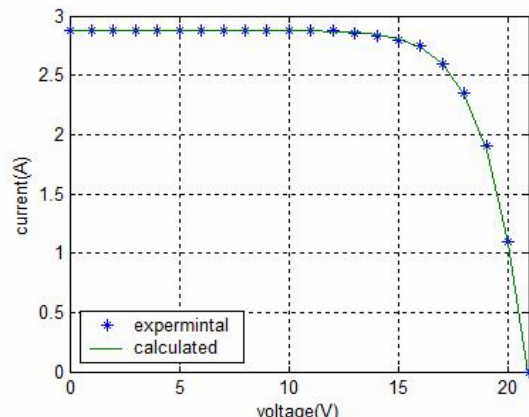


Fig. 7 V-I Char. of the shell SP75 model (monocrystalline silicon) at $V_o=21.0$, $I_{sc}=2.88$, $G=600$

Table 2. Evaluation of NRMSE(%) for KC200GT Module

VO	ISC	NRMSE(%)	ERROR% OF MAX POWER
32.9	8.21	0.75318	1
31.1	3.28	1.5	0.07
29.75	8.29	1.2	0.8

Table 3 gives the evaluated nRMSE(%) corresponding to the theoretical I– V curves based on the proposed model and experimental data for SP75 at different environmental conditions. It is seen that the accuracy of the estimated values of maximum power are in good tolerance for SP75 at different environmental conditions. It can be observed that the theoretical I–V curves are sufficiently accurate for the experimental data. This proves the validity of the proposed parameter identification technique for PV modules.

Table 3. Evaluation of NRMSE(%) for SP7 Module

VO	ISC	NRMSE(%)	ERROR% OF MAX POWER
21.7	4.8	0.60547	0.41826
21.0	2.88	1.0012	0.11714
21.3	3.84	0.58	1.5

The superiority of the proposed method over than other methods can be presented as shown in Table 4. The proposed MPPT algorithm has an ability to detect MPP of any PV independent on its technologies and size. But, FL and ANN are module dependent. The proposed algorithm has the least value of MPP error compared with others algorithms. The proposed method requires measurement of the short circuit current and open circuit only where, the measuring of current and voltage is typically easier and more reliable than sensors that measure the light level.

Table 4: Comparison between Different Algorithms of MPP

	Fraction Open circuit voltage	Fraction Short circuit current	P@O	I@C	ANN	FL	Proposed
PV array dependent	No	No	No	No	Yes	Yes	No
Error % in MPP	>10%	>10%	<5%	<3%	<2%	<2%	<1.5%
Convercion Speed	medium	medium	Varies	Varies	Fast	Fast	Fast

6. Conclusion

An algorithm for modeling and Maximum Power Point (MPP) detection of a PV module has been developed. The proposed algorithm requires less information to get an accurate model and maximum power point. In this work, the proposed algorithm uses open circuit voltage and short circuit current only as input data. The initial values of the model parameters is estimated by extracting the panel parameters from datasheet values, and the obtained values have been used in the proposed algorithm. PV model and (MPP) are estimated using the Newton Raphson method. From the present analysis, one can draw the following main conclusions:

- 1- The proposed algorithm uses open circuit voltage and short circuit current only as input data.
- 2 The proposed algorithm give initial values of PV model and (MPP) sufficiently near the desired and the Newton-Raphson iterative method converges remarkably quickly.
- 3- The proposed equations which are expressed in a PV system, allow one to calculate a PV model parameters and (MPP) without relying on the experimental I-V.
- 4- It is seen that the accuracy of the estimated values of maximum power are in good tolerance for different manufacturer models shell SP75 model (mono-crystalline silicon and shell KC200GT model (multicrystal)
- 5- The calculated (I-V) curves based on the proposed method are in good agreement with the experimental data for different manufacturer models shell SP75 model (mono-crystalline silicon and shell KC200GT model (multicrystal).

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