

# Simulation and Experimental Results for a Single Diode Photovoltaic Model using Newton-Raphson Parameter Estimation Method

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**Abstract.** Modeling a photovoltaic (PV) module with a single diode model is the simplest and most popular model for representing the commercial PV products. However, to achieve a high accuracy PV model, several parameters are involved. Unfortunately, there are only some parameters provided from the manufacturers. This paper proposes the method to estimate these parameters using MATLAB program. There are five parameters needed for simulation in MATLAB, which are the photon current ( $I_{ph}$ ), diode ideality factor ( $a$ ), reverse saturation current ( $I_o$ ), series resistance ( $R_s$ ) and shunt resistance ( $R_{sh}$ ). Among these parameters, series and shunt resistances are the most difficult and thus the Newton-Raphson (NR) iterative method is used for capturing the values for these parameters in MATLAB. A 5 W monocrystalline module was used as a reference module in this work. It was found that the NR method provided a fast and reliable computing method for estimating these two parameters of the PV module. Finally, five parameters estimation with NR and adapted ideality factor method is highly recommended for high accuracy estimation of electricity generation from a single diode solar PV model.

## Keywords:

Modeling, monocrystalline, Newton-Raphson (NR), series resistance, shunt resistance

## 1. Introduction

The global increasing demand of photovoltaic (PV) modules is such a driving force that the manufacturers are required to design the modules with standard parameters. To estimate electricity generated from a PV module, it is important to understand the environmental parameters such as the weather and temperature, as well as, the parameters of a module itself such as series resistance ( $R_s$ ) and shunt resistance ( $R_{sh}$ ). In the field of modeling and manufacturing PV modules, the know-how and familiarity of these two resistances are crucial.

Generally, the  $R_s$  and  $R_{sh}$  are not explicitly given by the manufactures. Many researchers proposed that  $R_s$  is the

inverse of the slope of the I-V curve at the open circuit voltage point and  $R_{sh}$  is the inverse of the slope of the I-V curve at the short circuit point as expressed in (1) and (2), respectively [1].

$$R_s = \left. \frac{dV}{dI} \right|_{I=0}^{V=V_{oc}} \quad (1)$$

$$R_{sh} = \left. \frac{dV}{dI} \right|_{V=0}^{I=I_{sc}} \quad (2)$$

However, not all the manufactures can provide the standard I-V and P-V curves in their data specification sheets [2]. The module used in this research is that kind of product and it is not accessible to measure the slope using the I-V curve attached with the manufacturing data sheet. Therefore, the equations (1) and (2) could not be used to determine  $R_s$  and  $R_{sh}$ . Moreover, this method for finding  $R_s$  and  $R_{sh}$  usually generate errors in measuring the slope. However, many literatures highlighted this method as the easiest way to approximate these two resistances. Theoretically, there are three causes to conduct  $R_s$ : the flow of current via emitter and base of the PV cell, resistivity due to the metal contacts such as fingers, bus bars, soldering joints and silicon slab and finally the resistivity due to the front and back metal surfaces. Apart from the ideal case, it is inevitable the losses due to series and shunt resistances. Higher limit in  $R_s$  and extremely low  $R_{sh}$  can cause the I-V curve shift to the left and thereby decrease the fill factor of the solar PV module. Consequently, the efficiency drops because the fill factor is directly proportional to the efficiency of the module.

$R_{sh}$  is mainly related to the manufacturing defects of the PV material. The fabrication process of the PV material is a direct concern with this parameter. Theoretically,  $R_{sh}$  is comparatively larger than  $R_s$ ; so,  $R_{sh}$  was simply ignored and the model was simplified [3], [4]. However, This  $R_s$ -model can lead to the poor estimation for the maximum power and the open circuit voltage [5]. Jung and Ahmed (2012) fixed the values of  $R_s$  and  $R_{sh}$  to reduce the whole step of finding these complex parameters [6]. Harrag and

Nomenclature	
$I$	Output current (A)
$V$	Output voltage (V)
$I_{sh}$	Shunt current (A)
$R_s$	Series resistance ( $\Omega$ )
$R_{sh}$	Shunt resistance ( $\Omega$ )
$I_o$	Reverse saturation current (A)
$I_{on}$	Reference reverse saturation current (A)
$a$	Diode ideality factor (1.2)
$I_d$	Diode current (A)
$I_{phn}$	Reference photon current (A)
$I_{ph}$	Photon current (A)
$T$	Operational temperature (K)
$T_n$	Reference temperature (25 °C+273.15)
$G_n$	Reference irradiance (1000 W/m <sup>2</sup> )
$G$	Operational irradiance (W/m <sup>2</sup> )
$V_{mp}$	Voltage at maximum power point (V)
$I_{mp}$	Current at maximum power point (A)
$V_t$	Thermal voltage of a solar cell or module (V)
$V_{tn}$	Reference thermal voltage (V)
$K_i$	Temperature coefficient of short circuit current (0.002 A/K)
$V_{oc}$	Open circuit volatage (V)
$V_{ocn}$	Reference open circuit voltage (V)
$k$	Boltzmann constant (1.3806503e-23 J/K)
$q$	the charge of an electron (1.60217646e-19 C)
$I_{sc}$	Short circuit current (A)
$I_{scn}$	Reference short circuit current (A)
$E_g$	Band gap energy of monocrystalline (1.12 eV)
$N_s$	Number of cells connected in series in a module (36)
$P_{max\_datasheet}$	Maximum power by datasheet
$P_{max\_model}$	Maximum power modeled by NR
$a_{adapted}$	Adapted ideality factor (factor)
STC	Standard Test Condition (T=25 °C+273.15 G=1000 W/m <sup>2</sup> )
NR	Newton-Raphson iterative method
MPP	Maximum power point

Messalti (2017)Harrag and Messalti (2017) applied Particle Swarm Optimization (PSO) method while Sarjila, Ravi, Edward, Kumar and Prasad (2016) used Gravitational Search Algorithm (GSA) optimization techniques to solve the transcendental nature of solar PV equations to extract these two parameters [7], [8]. Some literatures emphasized on the more precise methods with regard to these two resistances by numerical methods. Among those methods, the Newton-Raphson (NR) iterative method is one of the most powerful and widely applied because of its fast computation speed in finding roots for transcendental equations [6], [9]-[11]. In this paper, the performance analysis of an ideal single diode PV module is firstly presented. Secondly, the method to estimate values for PV parameters by NR method in MATLAB will be discussed. Thirdly, I-V and P-V characteristic curves are simulated at STC ( $G=G_n=1000 \text{ W/m}^2$  and  $T=T_n=25 \text{ °C}$  or 298.15 K). This estimated and simulated  $P_{max}$  at STC will be compared with the data sheet  $P_{max}$ . After that, the result from simulated model with different temperature is compared with the experimental results. Finally, five parameters estimation used for a single diode PV module is proposed by using the Newton-Raphson (NR) iterative with modified ideality factor method.

## 2. Ideal and Non-ideal Single Diode PV Module

An ideal and non-ideal single diode PV model can be compared as shown in Figs. 1 and 2, respectively. In the case of an ideal PV model, the effects of all the resistances which cannot be avoided in practice are neglected. Thus, the output current generated by an ideal solar cell is the subtraction of the diode current from photoelectric current according to (3). It means that all the photon fluxes hit the cell transverse supplied current to the load without having barriers.

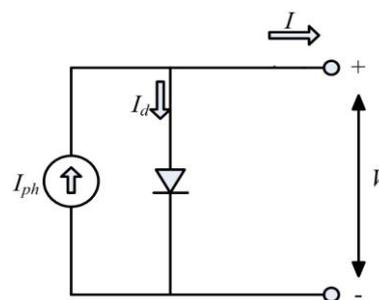


Fig. 1: An ideal single diode PV model

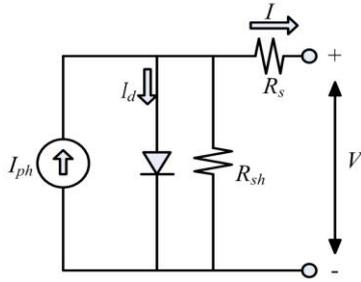


Fig. 2: A Non-ideal single diode PV model

$$I = I_{ph} - I_d \quad (3)$$

Where  $I_d$  is the diode current and can be written as in (4). This equation (4) is called the Shockley diode equation.

$$I_d = I_o \left[ \exp\left(\frac{V + IR_s}{V_t a}\right) - 1 \right] \quad (4)$$

$$V_t = \frac{kT}{q} \quad (5)$$

Where  $V_t$  is the thermal voltage of a solar cell, however,  $V_t$  will be given as shown in (6) for a solar PV module.

$$V_t = \frac{N_s kT}{q} \quad (6)$$

In a real situation, the influences of parasitic resistances still exist as shown in Fig. 2. The final output current of a solar cell after subtracting the losses due to resistances is presented in (7) and (9).

$$I = I_{ph} - I_d - I_{sh} \quad (7)$$

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \quad (8)$$

$$I = I_{ph} - I_o \left[ \exp\left(\frac{V + IR_s}{V_t a}\right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (9)$$

### 3. Modeling of a Single Diode PV Module in MATLAB

The increase of global installed capacity of solar-PV systems needs powerful simulation tools for researchers and engineers. Most studies have been focused on the modeling of a single diode model, but with various parameter estimating methods. Nowadays, many commercial softwares such as PV\*sol and PVsyst® are popular to use as the simulation tools. However, these tools are not efficient for the deep understanding of complex parameters of the PV module. The MATLAB is used as a simulation tool in this paper because it is a powerful tool to do a more precise simulation and estimation [12]. Moreover, in MATLAB/ SIMULINK, many sophisticated simulations are capable to simulate and model the PV cell as well as the

module or the array. In the terms of solar PV systems, stand-alone as well as grid-connected systems can be designed and simulated efficiently in MATLAB [12]-[16].

#### 3.1 PV Parameter Estimation by NR method

This section proposes the algorithm to calculate the most complex parameters:  $R_s$  and  $R_{sh}$  by using Newton-Raphson iterative method via MATLAB. The purpose of the calculation process is to give a pair of four unknown parameters that can generate the maximum power output of the PV module. The NR method is widely used due to its simplicity as well as fast mode of convergence for solving nonlinear equations [8]. Moreover, it is a powerful method of differential calculus but its process needs an initial guess for the starting point. The disadvantage of this method is the initial guess of the starting point that should be selected carefully; otherwise, the calculation will not converge.

Based on the parameters which cannot be accessed from the manufacturing datasheet, many literatures have used the terms “five parameters estimation method” for parameter extraction of a single diode PV model and “seven parameters estimation method” for parameter extraction for the two diode PV model. Most commercial PV manufactures usually provide temperature coefficient of the short circuit current ( $K_i$ ) in their data sheet but the module in this research is a small 5 W monocrystalline module with the lack of this data. Hence, precisely, six parameters are needed to be estimated for this research to model a single diode PV model in MATLAB. These are  $K_i$ ,  $a$ ,  $R_s$ ,  $R_{sh}$ ,  $I_{ph}$  and  $I_o$ . In this research, the first two parameters will be fixed by referencing the previous literatures and the last four parameters will be estimated by the NR method. Hence, the diode ideality factor ( $a$ ) is fixed to 1.2 for monocrystalline module [9]. Similarly,  $K_i$  is adopted as 0.002 A/K for monocrystalline based on previous research [17].

Theoretically, the diode ideality factor ( $a$ ) varies from 1 to 2 [18].  $a$  is a measurement of how closely the diode follows the ideal diode equation and is directly related to the types of recombination of photovoltaic devices [19]. In addition, the values of  $a$  is dependent on the PV materials used, as well as, representing some influential effects caused by environmental conditions, for instance, solar irradiance and temperature [7]. However,  $a$  has a stable feature in a single diode PV module [6].

#### 3.2 Initial guess of $R_s$ and $R_{sh}$

In NR method,  $R_s$  is started from 0 and increased by 0.01 until it reached Maximum Power Point (MPP) condition. Here, the maximum and minimum limits of  $R_s$  and  $R_{sh}$  are defined as shown in (10) and (11), respectively [20]. The maximum and minimum limits in (10) and (11) are used as the indicators to check the validation of the algorithm. A general overview over the algorithm is described as in Fig. 3.

$$R_{s\_max} = \frac{(V_{ocn} - V_{mp})}{I_{mp}} \quad (10)$$

$$R_{sh\_min} = \frac{V_{mp}}{I_{scn} - I_{mp}} - R_{s\_max} \quad (11)$$

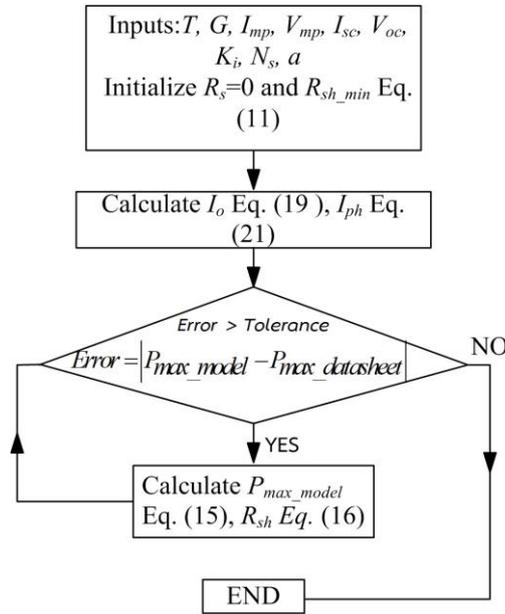


Fig. 3: Algorithm of the NR method

If (9) is applied for a solar PV module at maximum power point (MPP), the current at maximum power point can be derived as shown in (12).

$$I_{mp} = I_{ph} - I_o \left[ \exp \left( \frac{V_{mp} + I_{mp} R_s}{V_t a} \right) - 1 \right] \quad (12)$$

$$\frac{V_{mp} + I_{mp} R_s}{R_{sh}} \quad (13)$$

$$P_{max\_datasheet} = V_{mp} I_{mp} \quad (13)$$

$$P_{max\_datasheet} = P_{max\_model} \quad (14)$$

$$P_{max\_model} = V_{mp} I_{mp} \quad (15)$$

By substituting (12) in (13) and equating (13) with (15), the shunt resistance that matches up with MPP can be deducted as presented in (16).

$$I_{on} = \frac{I_{scn}}{\left[ \exp(V_{ocn}/aV_{tn}) - 1 \right]} \quad (17)$$

$$V_{tn} = \frac{N_s k T_n}{q} \quad (18)$$

$$I_o = I_{on} \left( \frac{T}{T_n} \right)^3 \exp \left[ \frac{q E_g}{N_s a k} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right] \quad (19)$$

$$I_{phn} = \frac{(R_s + R_{sh})}{R_{sh}} \times I_{scn} \quad (20)$$

$$I_{ph} = \left[ I_{phn} + K_i (T - T_n) \right] \frac{G}{G_n} \quad (21)$$

$$I_{sc} = (I_{scn} + K_i dT) \frac{G}{G_n} \quad (22)$$

$I_{on}$ ,  $I_o$ ,  $I_{phn}$ ,  $I_{ph}$  and  $I_{sc}$  are needed to be calculated prior to the iterative process from (18)-(22). In the iterative process,  $R_s$ ,  $R_{sh}$ ,  $I_{ph}$  and  $I_o$  will be updated to satisfy the MPP. The importance of the NR method is to take out exactly one pair of these parameters matching with the MPP by tangentially increasing the values to reach the MPP. The original formula of the NR method can be written as shown in (23). Thus, (9) will be substituted for adaptation of the NR method as expressed in (24)-(26)

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (23)$$

$$I_{i+1} = I_i - \frac{f(I_i)}{f'(I_i)}, \quad i \geq 0 \quad (24)$$

$$f(I_i) = I_i - I_{ph} + I_o \left[ \exp \left( \frac{V + I_i R_s}{V_t a} \right) - 1 \right] \quad (25)$$

$$+ \frac{V + I_i R_s}{R_{sh}} = 0$$

$$R_{sh} = \frac{V_{mp} (V_{mp} + I_{mp} R_s)}{\left( V_{mp} I_{ph} - V_{mp} I_o \left[ \exp \left( \frac{V_{mp} + I_{mp} R_s}{V_t N_s a} \right) - 1 \right] - P_{max\_datasheet} \right)} \quad (16)$$

$$f'(I_i) = 1 + \frac{I_o R_s}{V_t} \left[ \exp\left(\frac{V + I_i R_s}{V_t a}\right) \right] + \frac{R_s}{R_{sh}} = 0 \tag{26}$$

Where  $I_i$  and  $I_{i+1}$  are the output current of the PV model at the  $i^{th}$  and  $i+1^{th}$  iterative steps. According to the rule of NR, the output current of the PV model at the  $i+1^{th}$  iterative step is equal to the output current of the PV model at the  $i^{th}$  iterative step and then the iteration is executed end by generating the values of four parameters. As long as the output currents of the module at the  $i^{th}$  and  $i+1^{th}$  iterative steps are not equal, the iteration will be repeated. For this reason, this kind of repeating the loops can efficiently be achievable in MATLAB. The tolerance of the difference between the  $P_{max-model}$  and the  $P_{max-datasheet}$  is 0.001 W. The parameters estimated by the NR method that match with the MPP under Standard Test Condition (STC) and the input parameters are listed as in Table 1 and Table 2, respectively. Among the parameters listed in Table 1, a pair of  $R_s$  and  $R_{sh}$  will firstly be discussed by comparing the slope of simulated I-V curve and experimental I-V curve.

$R_s$ ( $\Omega$ )	$R_{sh}$ ( $\Omega$ )	$I_{ph}$ (A)	$I_o$ (A)
2.52	1,322.61	0.32	1.24e-9

Table 1: Parameters estimated by NR at STC

$V_{ocn}$ (V)	21.5	Datasheet value
$I_{scn}$ (A)	0.32	Datasheet value
$V_{mp}$ (V)	17.5	Datasheet value
$I_{mp}$ (A)	0.29	Datasheet value
$N_s$ (no.)	36	Datasheet value
$a$ (factor)	1.2	Previous literature [8]
$K_i$ (A/K)	0.002	Previous literature [19]

Table 2: Input parameters for NR method

### 3.3 Simulation in MATLAB

The I-V and P-V characteristic curves of 5 W monocrystalline module at different irradiances and same temperature can also be simulated in MATLAB by using the parameters estimated in Table 1, which are depicted in Figs.4-5.

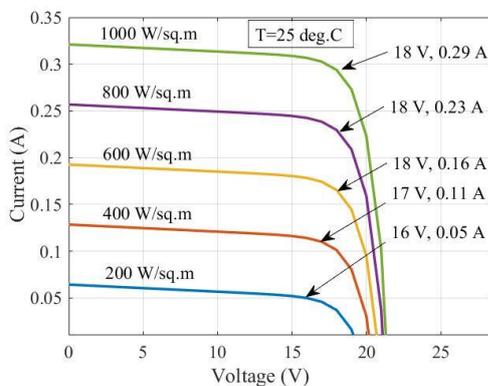


Fig. 4: Simulation of I-V characteristic curves

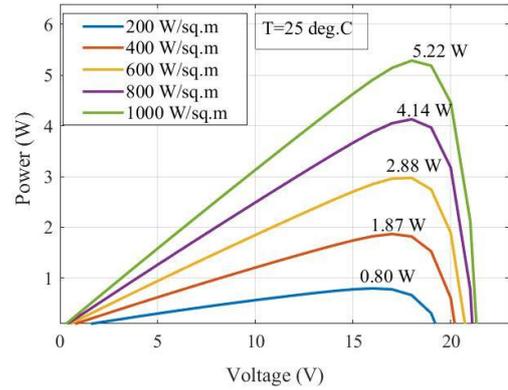


Fig. 5: Simulated P-V characteristic curves

According to Fig. 5, it is observed that the maximum output power of the 5 W PV module varies from 0.80 W at the irradiance level of 200W/m<sup>2</sup> to 5.22 W at the irradiance level of 1000 W/m<sup>2</sup>. At STC, the simulated output power is 5.22 W; therefore, the estimated  $P_{max}$  is merely 2.3% larger than the upper limit of the datasheet  $P_{max}$  which is 5 W $\pm$ 2%. However, it is still 6.1% larger than the lower limit. In this case, NR method with four parameters estimation is used. To reduce the error up to less than 1 %, the five parameters estimation with NR and adapted ideality factor will be proposed in the next section.

### 4. Experimental Setup and Results

The 5 W monocrystalline PV module was tested from 10 a.m. to 3 p.m. on every sunny day during May and June in 2017 at Khon Kaen University, Thailand. The module was manually tracked the sun to make the surface of the module directly perpendicular to the sun ray. In other words, the generated  $P_{max}$  is always at the MPP. Equipment used in this experiment is shown in Fig. 6. The specification of the module is shown in Table 3. The  $G$  is calculated based on the measured  $I_{sc}$  and  $T$  using (27) by assuming  $I_{scn}=I_{phn}$  and  $I_{sc}=I_{ph}$ .

$$I_{ph} = \frac{G}{G_n} [I_{phn} + K_i(T - T_n)] \tag{27}$$

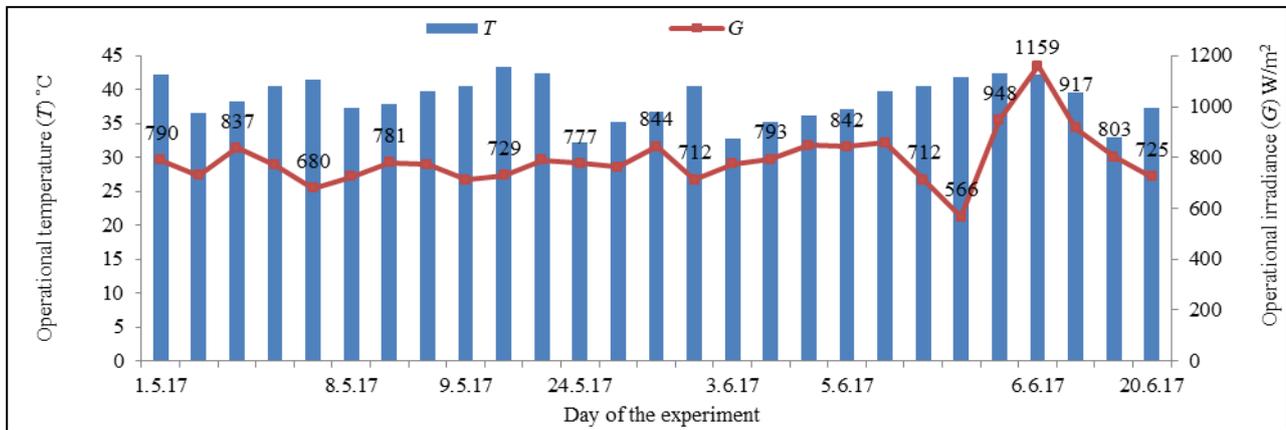


Fig. 6: Equipment used in the experiment

Manufacture	Sun Solar Ecotech
Type	Monocrystalline
Max. power Output ( $P_{max}$ )	5 W $\pm$ 2 %
Open circuit voltage ( $V_{oc}$ )	21.5 V
Short circuit current ( $I_{sc}$ )	0.32 A
Maximum power voltage ( $V_{mp}$ )	17.5 V
Maximum power current ( $I_{mp}$ )	0.29 A
Maximum system voltage (V)	1000 VDC
Dimension (mm)	193*245*18

**Table 3:** The specification of the PV module

Although irradiance level was normally low during these months, it exceptionally reached 1,159 W/m<sup>2</sup> with  $T=42.3^{\circ}\text{C}$  at 1 p.m. on 6<sup>th</sup> June 2017 as in Fig. 7. 1,159 W/m<sup>2</sup> irradiance was needed to be adjusted as 1000 W/m<sup>2</sup> as the STC condition. Therefore, the conditions of  $G=1000$  W/m<sup>2</sup> and  $T=42.3^{\circ}\text{C}$  were used to simulate the I-V and the P-V curves via MATLAB and the results then were used to compare with the experiment at 1 p.m. on 6<sup>th</sup> June, 2017.



**Fig. 7:** Results of the experiment

**5. Comparison between Simulation and Experiment**

The I-V and the P-V curves obtained from the experimental test taken at 1 p.m. on 6<sup>th</sup> June, 2017 were compared with the simulated results from MATLAB as shown in Figs. 8 and 9, respectively. All the conditions in the simulation in MATLAB were imitated to the real environmental conditions of 1p.m. on 6<sup>th</sup> June, 2017 when  $T=42.3^{\circ}\text{C}$  and  $G=1000\text{W/m}^2$ . Here, Table 4 shows the input parameters for MATLAB simulation and the reference parameters for the module is the same as in Table 2.

**Table 4** Input parameters for simulation in MATLAB

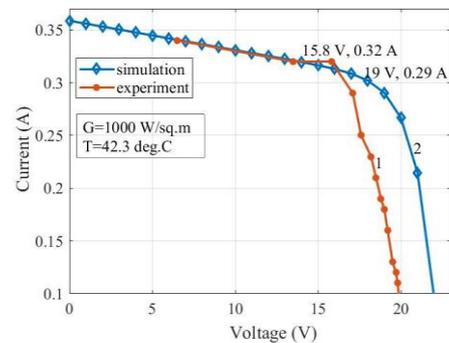
Measured		Calculated by NR			
$T (^{\circ}\text{C})$	$G (\text{W/m}^2)$	$R_s (\Omega)$	$R_{sh}(\Omega)$	$I_{ph} (\text{A})$	$I_o(\text{A})$
42.3	1000	5.17	360.35	0.36	1.55e-9

According to Fig. 8, the slope of the I-V curve of experiment is exactly the same as the curve of the simulation with the NR method. However, as shown in Fig. 9, the generated maximum powers were 5.06 W for experiment and 5.51 W for the simulation. Thus, the estimated power output is around 8 % higher than the experimental one. The reason is the diode ideality factor ( $a$ ) is assumed constant in this research. This parameter greatly

influences the maximum power output. However, in terms of the estimation of the maximum power output from a specific PV module, the error 8% is significantly larger by leading the controversial point in the accuracy of the model. The four parameters estimation method is, therefore, insufficient to build the PV model with a single diode as well as to predict the electricity generated. In this four parameters estimation model using the NR method, the value of diode ideality factor was fixed; however, the diode ideality factor is dependent on other parameters as shown in (28). As the temperature is higher, the difference is larger. Thus the adapted diode ideality factor under operating temperature ( $T$ ) is needed, which can be calculated by using (28) in MATLAB.

$$a_{adapted} = \frac{V_{mp} + I_{mp}R_s}{V_t \ln \left( \frac{I_{ph} - I_{mp} - \frac{V_{mp} + I_{mp}R_s}{R_{sh}}}{I_o} + 1 \right)} \quad (28)$$

; where  $V_t = \frac{N_s k T}{q}$  in which  $T$  is  $42.3^{\circ}\text{C}$



**Fig. 8:** Comparative I-V curves between simulation and experiment

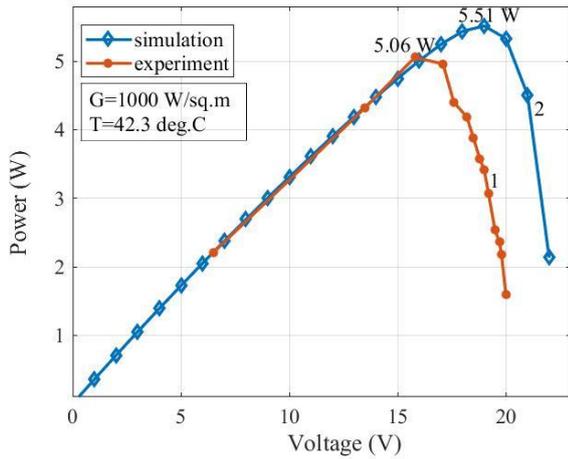


Fig. 9: Comparative P-V curves between simulation and experiment

In (28), the values of  $I_o$  are varied from  $1e-05$  to  $1e-10$ . The values of  $I_{ph}$ ,  $R_s$  and  $R_{sh}$  are in accordance with Table 4 and  $V_{mp}$  and  $I_{mp}$  are the reference parameters obtained from the datasheet as described in the specification of the module in Table 3. The estimated values of the adapted diode ideality factor are listed in Table 5.

$I_o$	$1e-05$	$1e-06$	$1e-07$	$1e-08$	$1e-09$	$1e-10$
$a_{adapted}$	2.3	1.8	1.5	1.3	1.1	1

Table 5: The adapted ideality factor values

From Table 5, the adapted diode ideality factor varies from 1 to 2.3. By simulating and modeling in MATLAB, it was found that the value of adapted diode ideality factor ( $a_{adapted}$ ) 1.8 was the value that satisfies the prediction of maximum power output for the model and the comparisons of simulated results and experimental results are shown in Figs. 10 and 11, respectively.

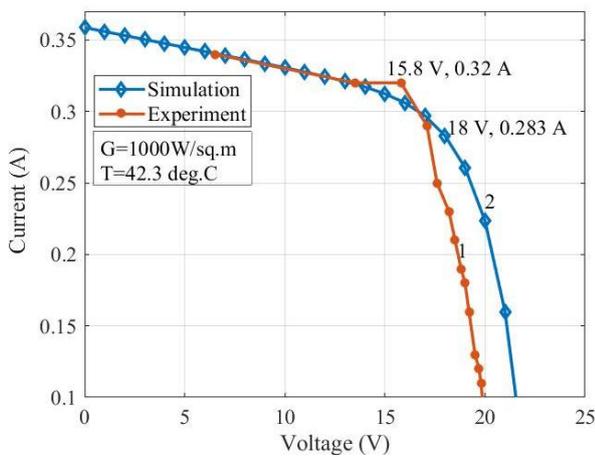


Fig. 10: Comparison of the I-V curves between the MATLAB simulation and the experiment

Fig. 10 shows the values of maximum operating current ( $I_{mp}$ ) and the maximum operating voltage ( $V_{mp}$ ) that are correspondent with the maximum power output ( $P_{max}$ ) described in Fig. 11 under the irradiance ( $G$ ) of  $1000 \text{ W/m}^2$  and the temperature ( $T$ ) of  $42.3 \text{ }^\circ\text{C}$ . The curve No.1 is the experimental curve and the curve No. 2 is the simulated I-V curves in MATLAB. In this final method of NR and adapted diode ideality factor method, the error was reduced significantly from 8% to 0.6%.

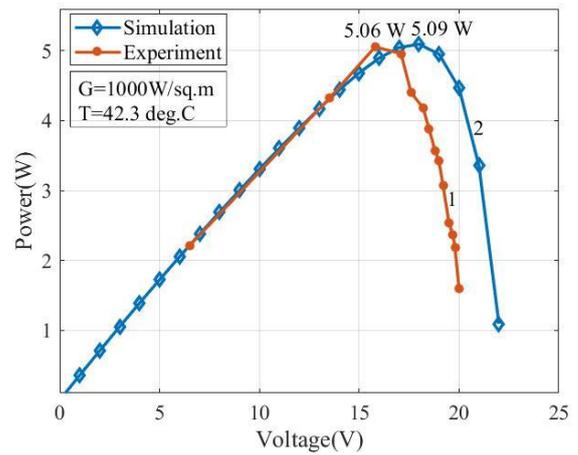


Fig. 11: Comparison of the P-V curves between the MATLAB simulation and the experiment

According to Fig. 11, it can be seen that the estimated power output from a single diode solar model in MATLAB by using the model of five parameters estimation based on the NR method and adapted diode ideality factor method reduces errors of the maximum power output from 8% to 0.6%.

## 6. Conclusion

This paper proposes method to develop a high accuracy single diode photovoltaic (PV) model in MATLAB using the Newton-Raphson method and adapted diode ideality factor method. The results showed that the proposed method could provide high accuracy model with low error of 0.6% at the maximum power point when compared to the data sheet and the practical experiment under real environment.

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