

# Simulation of Current-Voltage (I-V) and Power-Voltage (P-V) Characteristics of PV Module using Single-Diode Model in Irradiance and Temperature Effects

Mya Ei Mon<sup>1</sup>, Nay Win Zaw<sup>2</sup>

**Abstract---** This paper simulates the mathematical model of the PV (photovoltaic) module based on the MATLAB script file with all the parameters are involved. Modeling this device environmental factors such as irradiation and temperature are used as input variables. The output of the PV module varies depending on the environmental factors. Any changes in the inputs immediately implies changes in outputs. Physical parameters (series and shunt resistance, ideality factor, temperature coefficient of current and voltage, etc.) are significant effects on the operating curves of solar PV module. The aim of this modeling is to study the nature of nonlinear outputs of PV panel and to extract the physical unknown parameters for a given module. The chosen model is the single-diode model with both series and shunt resistances for precise output and investigates all parameters influence on solar PV module operation and focus on a program developed in MATLAB/M-file of 50W PV module. In the result of simulation the voltage, current, and power of PV panel decreased when the solar irradiance decreased and also they are increased when the temperature decreased. When compared the two results of the program simulation results and manufacturer' data sheets are found the two are identical at STC condition.

**Index Terms---** Solar energy, PV module, I-V and P-V characteristics, Irradiance, Temperature

## I. INTRODUCTION

Valuable energy can extract from our surroundings by several ways. These include energy extraction from sunlight, wind, biomass, sea levels, etc. All these ways are renewable in nature. The energy source itself renews, which can provide energy forever. Among all renewable energy strategies, photovoltaic system has own several fundamental advantages compare to others. By using semiconductor devices, solar

energy has identified as a static, movement-free and quiet alternative energy which can result to a long-term and low maintenance cost renewable system.

Solar cells can convert sun light into electricity directly. That produces DC voltage and DC electricity. A PV module is comprised many solar cells that are connected in series or parallel depends on the desired amount of voltage or current. A typical PV cell can produces 0.5V (2-3W). The PV module is the fundamental conversion unit of a PV generator system. So, it is necessary to model the PV module for the design and simulation of maximum power point tracking (MPPT) for PV system applications since PV module has non-linear characteristics. For a given environmental conditions, there is Maximum Power Point (MPP), an optimal point on the V-I curve, where maximum power output is achieved. So, at the MPP the efficiency will be optimized. The performance of the PV module is specified under Standard Test Condition (STC), where the irradiance is 1000W/m<sup>2</sup>, module temperature is 25°C and air mass is 1.5. This paper presents the modeling method and simulation of photovoltaic (PV) module. The parameters for the PV module are based on the manufacturers' data sheets values.

## II. MATHEMATICAL MODELING OF A ...PV MODULE

A solar cell is a basic unit of a solar module. A PV module is comprised many solar cells in series and parallel. For consider only a single solar cell, it can be modeled by utilizing a current source, a diode and two resistors. This model represents a single diode model of a solar cell.

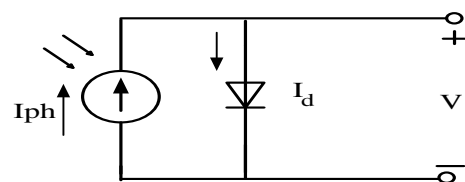


Fig.1. Ideal single-diode model

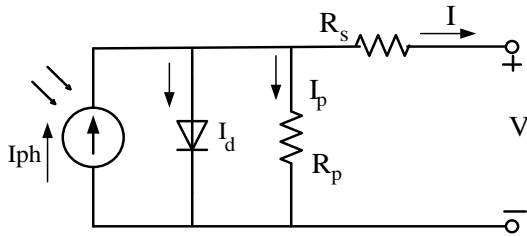


Fig.2. Single-diode model of a solar cell

A diode is connected in anti-parallel with the photocurrent in Figure 2 and the output current is obtained by Kirchhoff's law;

$$I = I_{ph} - I_d - I_p \quad (1)$$

Where,  $I_{ph}$  is the photocurrent,  $I_p$  is the current in the shunt resistor, and  $I_d$  is the diode saturation current and is given by the equation;

$$I_d = I_o [\exp(\frac{V}{A.N_s.V_t}) - 1] \quad (2)$$

Where,  $V$  is the voltage imposed on the diode.  $I_o$  is the saturation current of the diode,  $V_t$  is the thermal voltage of its exclusive dependence of temperature.  $N_s$  is the number of PV cells connected in series.  $A$  is the ideal factor of the diode and it depends on the PV cell technology. [2]

$$V_t = \frac{k.T_c}{q} \quad (3)$$

Where,  $T_c$  is the actual cell temperature (K),  $k$  is Boltzmann's constant ( $1.3805 \times 10^{-23}$  J/K) and  $q$  is Electron charge ( $1.6021 \times 10^{-19}$  C). So, the output current is

$$I = I_{ph} - I_o [\exp(\frac{V + IR_s}{A.N_s.V_t}) - 1] - \frac{V + IR_s}{R_p} \quad (4)$$

The power produced by a single PV cell is less and not enough for almost any applications. So, the cells may be configured in series and parallel features to increase the capability of overall PV systems. Equation (4) can be expressed as;

$$I = N_p I_{ph} - N_p I_o [\exp(\frac{V + IR_s}{A.N_s.V_t}) - 1] - \frac{N_p V + IR_s.N_s}{R_p.N_s} \quad (5)$$

Where,  $N_p$  as the number of cells connected in parallel,  $R_s$  and  $R_p$  are the series and shunt resistance of the solar cell.

### III. FINDING THE PARAMETERS

Modeling the PV devices, if the number of unknown parameters increases the results are away from being the ideal form. Most of the manufacturer's datasheets do not provide enough

information about the parameters which depends on weather conditions. There are five parameters ( $I_{ph}, I_o, A, R_s, R_p$ ) are considered depends on the irradiation and cell temperature. Ideality factor ( $A$ ) is chosen 1.3 for silicon. [2]

#### 1) Finding $I_{ph}$

To simply the model, the effect of shunt resistance is not considered since usually the shunt resistance  $R_p$  is large and the series resistance  $R_s$  is small. So, ignore the last term in (4) and the output current at STC conditions output current at the STC condition is;

$$I = I_{ph} - I_o [\exp(\frac{V}{A.N_s.V_t}) - 1] \quad (6)$$

When the PV cell is short-circuited;

$$I'_{sc} = I'_{ph} - I_{on} [\exp(\frac{0}{A.N_s.V_t}) - 1] \quad (7)$$

In ideal case,

$$I'_{sc} \approx I'_{ph} \quad (8)$$

Where,  $I'_{sc}$  is short circuit current and  $I'_{ph}$  is photocurrent and  $I_{on}$  is the reverse saturation current at STC conditions. Photocurrent or light generated current mainly depends on the solar radiation and cell working temperature, So

$$I_{ph} = \frac{G}{G_n} (I'_{sc} + K_i(T_c - T_n)) \quad (9)$$

Where,  $G$ :Irradiance( $W/m^2$ ),  $G_n$ :Irradiance at STC( $1000W/m^2$ ),  $T_c$ : cell temperature (K),  $T_n$ : Cell temperature at STC ( $25+273=298K$ ).  $K_i$  is coefficient temperature of current (A/K).

#### 2) Finding $I_o$

The solar cell has three points at STC conditions:

- (i) Voltage at open circuit condition  
( $I = 0, V = V'_{oc}$ )
- (ii) Current at short circuit condition  
( $V = 0, I = I'_{sc}$ )
- (iii) Maximum Power Point condition ( $V_{mp}, I_{mp}$ )

So, the following equation can be written as,

$$I = I_{ph} - I_o [\exp(\frac{V + IR_s}{A.N_s.V_t}) - 1] \dots\dots\dots(10)$$

For open circuit condition;

$$0 = I'_{ph} - I_{on} [\exp(\frac{V'_{oc}}{A.N_s.V_t}) - 1] \quad (11)$$

For short circuit condition;

$$I'_{sc} = I'_{ph} - I_{on} [\exp(\frac{I'_{sc}.R_s}{A.N_s.V_t}) - 1] \quad (12)$$

For maximum power point condition;

$$\dots\dots I_{mp} = I'_{ph} - I_{on} [\exp(\frac{V_{mp} + I_{mp}.R_s}{A.N_s.V_t}) - 1] \quad (13)$$

Where,  $V'_{oc}$  is open circuit voltage at STC condition. Since (-1) is too smaller than the exponential term it is neglect. Since  $I'_{sc} \approx I'_{ph}$ , Equation (11) will be

$$1111 0 \approx I'_{sc} - I_{on} [\exp(\frac{V'_{oc}}{A.N_s.V_t})] \quad (14)$$

$$I_{on} = I'_{sc} [\exp(\frac{-V'_{oc}}{A.N_s.V_t})] \quad (15)$$

The diode saturation current is directly influenced by environmental changes and it can be determined by the following mathematical equation;

$$I_o = I_{on} (\frac{T_c}{T_n})^3 \exp(\frac{q.E_g}{A.k} (\frac{1}{T_n} - \frac{1}{T_c})) \quad (16)$$

Where,  $E_g$  is the band gap energy for the silicon semiconductor which is between 1.1 and 1.12 eV.

### 3) Finding $R_s$ and $R_p$

Sometimes manufacturer' data sheets do not provided these values. But they are strongly affect the characteristics of solar modules. In this paper  $R_s$  and  $R_p$  values are extracted by setting the computed maximum power ( $P_{mp}$ ) is equal to the experimental one ( $P_{mp,ex}$ ) at STC conditions. Iterative solution method is also used to determine the  $R_s$  and  $R_p$  resistance values. There is only one point corresponding to a single value of  $R_s$  that satisfies the imposed condition  $P_{mp}$  at the maximum point. And then the  $R_p$  value is calculated as the following equation;

$$I_{mp} = \frac{P_{mp}}{V_{mp}} \quad (17)$$

$$I_{mp} = I'_{ph} - I_{on} [\exp(\frac{V_{mp} + I_{mp}.R_s}{A.N_s.V_t}) - 1] - \frac{V_{mp} + I_{mp}.R_s}{R_p} \quad (18)$$

Substituting  $I'_{ph}$  and  $I_{on}$  in (18);

$$R_p = \frac{V_{mp} + I_{mp}.R_s}{I'_{sc} - I'_{sc} [\exp(\frac{V_{mp} + I_{mp}.R_s - V'_{oc}}{A.N_s.V_t})] + I'_{sc} [\exp(\frac{-V'_{oc}}{A.N_s.V_t})]} \quad (19)$$

In determining  $R_s$  and  $R_p$ , the values are initially unknown and so initial guesses for  $R_s$  and  $R_p$  are necessary before the iterative process starts. The initial value of  $R_s$  assume zero. The initial value of  $R_p$  may be given by

$$R_p = R_{p,min} = \frac{V_{mp}}{I'_{sc} - I_{mp}} - \frac{V'_{oc} - V_{mp}}{I_{mp}} \quad (20)$$

Although  $R_p$  is still unknown, it surely greater than  $R_{p,min}$  and this is a good initial guess. [11] According to the iterative process  $R_s$  must be slowly incremented starting from  $R_s = 0$  and then  $R_p$  is calculated from the Equation (19) and requires several iterations until  $P_{mp} = P_{mp,ex}$ . Iterative processes stop at the computed maximum power ( $P_{mp}$ ) matches with the experimental result ( $P_{mp,ex}$ ). In this way  $R_s$  and  $R_p$  values are extracted.

## IV. NONLINEAR CHARACRERISTICS OF PV MODULE

The output of the PV module is unstable when weather conditions changes. So the proper nonlinear methods should be used for this unstable conditions. In this proposed model Newton-Raphson method is chosen.

$$X_{n+1} = X_n - \frac{f(X_n)}{f'(X_n)} \quad (21)$$

In which  $f(X_n)$  is the actual amount of the function,  $f'(X_n)$  is the derivation of the function,  $X_n$  is the current amount and  $X_{n+1}$  is the next amount. Newton-Raphson method needs one iteration loop which continues its operation, until the stopping point condition is met.

$$Error = \frac{|I_{n+1} - I_n|}{|I_{n+1}|} \times 100 \quad (22)$$

The two different ways for stopping condition is:  
 (1) Once the pre-specified numbers of iteration is done.  
 (2) Once the present error which can be obtained by using (22) is less than the pre-specified error.[5]

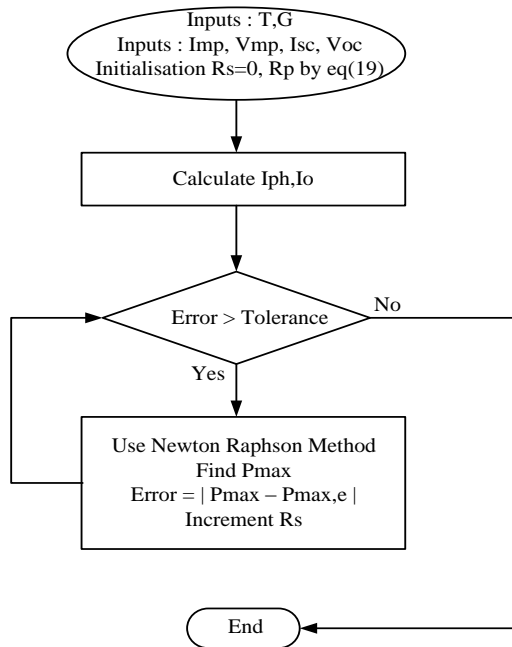


Fig.3. Iteration flowchart

Table I. Electrical Characteristics of RL-6P050/18 PV Module (50W)

Parameters	Values
Maximum Power (Pmax)	50W
Power Tolerance	±3%
Maximum Power Voltage (Vmp)	17.9V
Maximum Power Current (Imp)	2.79A
Open Circuit Voltage (Voc)	22.1V
Short Circuit Current (Isc)	2.97A
Maximum System Voltage	1000VDC
Operating Temperature	-40°C to + 85°C
Product Application	Class A
Weight	4.5KG
Dimension	760x510x30mm

All technical data at standard test conditions: AM = 1.5, G=1000W/m<sup>2</sup>, T=25°C.

## V. MATLAB SCRIPT FILE FOR PV MODULE

```

%%Information from the RL-6P050/18 solar
module datasheet %%
clear; clc;
Vocn = 22.1; %Nominal open-circuit voltage (V)
Iscn = 2.97; %Nominal short-circuit current (A)
Vmp = 17.9; %Maximum voltage (V)
Imp = 2.79; %Maximum current (A)
Eg = 1.12; % Band gap energy (eV)
Np = 1; % Number of parallel cells
Ns = 36; % Number of series cells
Pmax_e = Vmp*Imp; %Module maximum output
power (W)
Ki = 0.0013; % Temperature coefficient of current
(A/K)
Kv = -0.0079; %Temperature coefficient of voltage
(V/K)
Gn = 1000; % Nominal irradiance (W/m2)
Tn = 298; %Nominal operating temperature (K)
Tc = Ta+273; % Cell temperature (K)
%% Constants %%
k = 1.3805*10-23; % Boltzmann constant (J/K)
q = 1.6021*10-19; % Electron charge (C)
A = 1.3; % Diode ideality factor
Vtn = (k*Tn)/q; % Thermal junction voltage
(nominal)
Vt = (k*T)/q; % Thermal junction voltage (current
temperature)
G = input('G:'); % Actual irradiance (W/m2)
Ta = input('Ta:'); % Actual temperature (K)
%% Reference values of Rs and Rp %%
Rs_max = (Vocn-Vmp)/Imp;
Rp_min = Vmp/(Iscn-Imp)-Rs_max;
Rs = 0; % Initial value of Rs
Iph = (Iscn+Ki*(T-Tn))*G/Gn; %Nominal
photocurrent (A)
Ion = Iscn/ (exp (Vocn/(A*Ns*Vt))-1); %Nominal
diode saturation current (A)
Io=Ion*(Tc/Tn)3*exp((q*Eg)/(k*A))*(1/Tn-
1/Tc); % Diode reverse saturation current
(A)
error = Inf; % dummy value
%% Iterative process for Rs and Rp until Pmax =
Pmax,ex %%
while (error>0.001)
Rs = Rs+0.01; %Increment Rs
Rp=(Vmp+(Imp*Rs))/(Iscn(Iscn*exp((Vmp+(Imp
*Rs)-
(Vocn)/(A*Ns*Vt)))+(Iscn*exp(Vocn/(A*Ns*Vt)
))-Pmax_e/Vmp); % Shunt resistance
V = 0:0.1:50; % Voltage vector
I = zeros (1, size(V,2)); % Current vector
%% Solve with Newton-Raphson method %%
for j = 1:size(V,2)
    
```

```

g(j)=Np*Iph-I(j)-
Np*Io*exp((V(j)+(I(j)*Rs))/(A*Ns*Vt)-1)-
((Np/Ns*V(j)+(I(j)*Rs))/Rp;
while (abs(g(j))>0.001)
g(j)=Np*Iph-I(j)-
Np*Io*exp((V(j)+(I(j)*Rs))/(A*Ns*Vt)-1) -
((Np/Ns*V(j)+(I(j)*Rs))/Rp;
f(j) = -1-(Np*Io*Rs)/(A*Ns*Vt)*
exp((V(j)+(I(j)*Rs))/(A*Ns*Vt));
I_(j) = I(j) - g(j)/f(j);
I(j) = I_(j);
end
end
P = (Np*Iph-Io*(exp((V+I.*Rs)/(A*Ns*Vt))-1)-
(V+I.*Rs)/Rp).*V; % Calculate power
Pmax_m = max(P);
error = Pmax_m-Pmax_e;
end
    
```

### VI. SIMULATION RESULTS OF PV MODULE

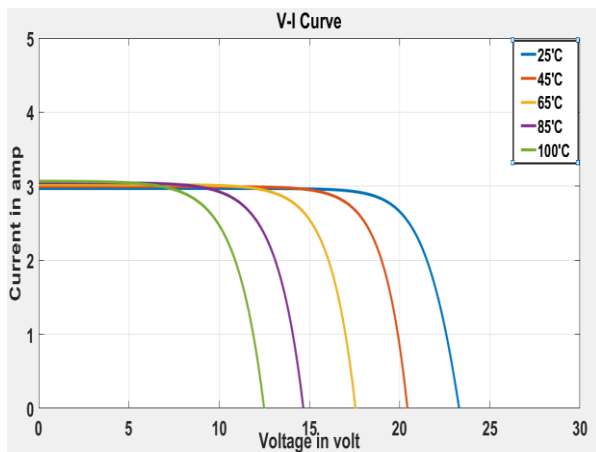


Fig.4. I-V curve with varying temperature and constant irradiance (G=1000W/m<sup>2</sup>)

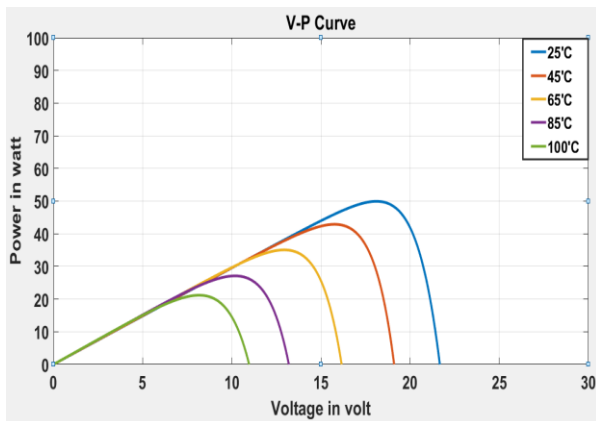


Fig.5. P-V curve with varying temperature and constant irradiance (G=1000W/m<sup>2</sup>)

Fig.4 and Fig.5 show the temperature increase around the solar cell has a negative impact on the power generation capability. When increasing the temperature (25°C to 100°C) (I-V) and (P-V) curves of PV module shifts towards the left and voltage drop drastically although the current is staying constant. This leads to net reduction in power output with increase in temperature. So, the maximum power also decreases with increase in temperature.

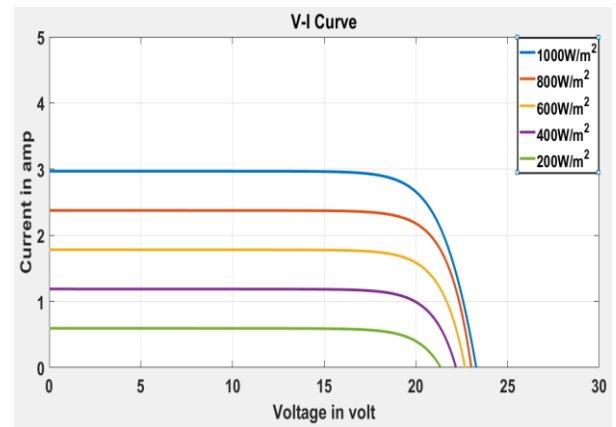


Fig.6. I-V curve with varying irradiance and constant temperature (T=25°C)

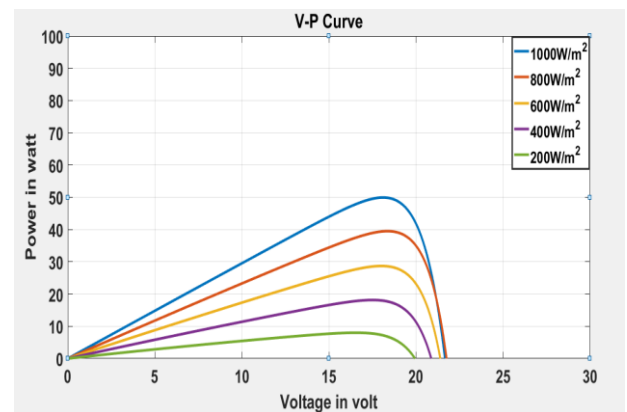


Fig.7. P-V curve with varying irradiance and constant temperature (T=25°C)

The effect of irradiance on the current-voltage (I-V) and power-voltage (P-V) characteristics can be seen in Fig.6 and Fig.7. When varying the irradiance (200W/m<sup>2</sup> to 1000W/m<sup>2</sup>) the current of the PV module increases sharply and the voltage also increase slightly. So, the photo generated current is directly proportional to the irradiance. As the effect on both the current and voltage is

positive and the effect on the power is also positive. Therefore, the more irradiation on the solar cell, the more power is generated.

## VII. CONCLUSION

The presented paper is the simulation of PV cell and module implemented under MATLAB/M-file. In this paper seen that the PV module output parameters can be varied depending on their cell temperature and irradiation. Also the simulation results are matched with the manufacturer' data sheets. It is importance to compute  $R_s$  and  $R_p$  because the experimental maximum output power does not match with the computed one in most case. So the iteration process and appropriate iteration method should be used for matching.  $R_s$  is iteratively increased until the match condition. In the proposed model show the result ( $P_{max} = 49.933\Omega$ ) is great accuracy with the datasheet ( $P_{mp,ex} = V_{mp} \times I_{mp} = 49.941\Omega$ ). Therefore, this model can be used to study all types of commercial PV modules and determine all necessary parameters under new conditions of irradiance and temperature and then, obtain the I-V and P-V characteristics.

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**Mya Ei Mon** received Bachelor of Engineering degree in Electronic Engineering from Hinthada Technological University in 2010. She is currently working toward the Master of Engineering in West Yangon Technological University.



**Nay Win Zaw** received Master of Engineering and PhD degree in Electronic Engineering from Mandalay Technological University. He worked as Professor in the Department of Electronic Engineering and worked as the Head of Department.