Characteristic Testing Of Simulation-Based Photovoltaic Models

U. Usman¹, Mochammad Apriyadi Hadi Sirad ²*

¹Department of Electrical Engineering, Ujung Pandang State Polytechnic, 90245, Indonesia
²Department of Electrical Engineering, Faculty of Engineering, Khairun University, Ternate, Indonesia
usman.ose@poliupg.ac.id, apriyadisirat@unkhair.ac.id

Abstract. This article explains the evaluation of the characteristics of PV implemented in Simulink / MATLAB. The implanted PV model is a model of one diode with a series resistor, a model of one diode with a series and parallel resistor, and a model of Two Diodes with a series and parallel barrier. The results obtained by the PV model with two diodes with series and parallel series are the best because it has an I_mp and V_mp error that opposes the data sheet compared to other models. Increasing the temperature will cause an increase in I_sc, but cause a decrease in V_oc. While decreasing from standard temperature will cause a decrease in I_sc but causes an increase in V_oc. This condition is the opposite of solar radiation changes, whereas I_sc will decrease dramatically with decreasing solar radiation. The diode ideal factor for the PV performance characteristics will cause a maximum increase in power P_m. However, it does not affect the values of I_sc and V_oc. While the greater the value of R_s will cause a decrease in P_m, but it does not affect the value of I_sc and V_oc. This is inversely proportional to the effect of the value of R_sh, while an increase in the value of R_sh will cause an increase in P_m but does not affect the value of I_sc and V_oc.

Keywords: PV models, PV characteristics, Modeling

1. Introduction

PV performance characteristics in general by looking at the I-V and or P-V curves. This curve provides how the relationship between voltage to current and voltage to PV output power, so that it can be determined the maximum power point is obtained in maximum current conditions and maximum voltage. PV performance is generally tested under standard conditions or Standard Test Condition (STC) i.e. at an average wavelength of 1.5 AM, normal radiation of 1000 W/m² and temperature of 25 °C[1].

Measurement of PV characteristics can basically be done directly on a PV but to meet the temperature and radiation requirements of the sun under STC conditions, these measurements usually require an environment that must be conditioned as in the conditions mentioned earlier and some special testing equipment, such as solar simulators. For this simulator is very limited and the price is expensive[1]. As for doing a simple test may not be enough to produce accurate measurements of these PV performance characteristics. Another cheaper and easier way is to model based on the
mathematical equations that apply to the PV, as some of them do,[1]–[5] that provide accurate results compared to direct measurements.

The ability to model PV output is key to PV performance analysis [5]. Based on the reference obtained modeling a PV there are four ideal models, one Diode model with series obstacles, one Diode model with series and parallel obstacles and two Diode models with series and parallel obstacles. In order to facilitate modeling can use a software one of them is MATLAB. This software is one of the popular software in the field of engineering today. In MATLAB there is a SIMULINK feature that can model mathematical equations. This feature will be used in this study to obtain PV characteristics, as performed by[6], [7], [8]. SIMULINK there are various toolboxes that can be used to string dynamic systems can also create multiple systems and sub systems, sub-sub systems and so on on a single page only [9].

Based on the above explanation of pv characteristics it can be stated that the output of the PV depends heavily on the solar radiation and the temperature that overrides the PV. Therefore it is very important to know the changes in standard conditions (radiation and temperature) to PV output for engineers to choose pv types for an application. In addition to radiation and temperature, other parameters affecting the output of pv modules are the ideal diode factors, series barriers and parallels.

2. Photovoltaic (PV)

Photovoltaic (PV) is a device/device that directly converts sunlight into electricity by utilizing photovoltaic effects. Photovoltaic effect is a phenomenon of the appearance of electrical voltage caused by the contact of two electrodes connected to the solid system or liquid when obtaining light energy. When light hits the surface of a solar cell, some photons of light are absorbed by semiconductor atoms to free electrons in the connection of type n semiconductors as well as type p from their atomic bonds. This phenomenon depends on the semiconductor material and on the wavelength of light. So that the electron becomes a free-moving electron. It is the transfer of these electrons that causes the onflow of electricity, as shown in the figure 1. The electric current raised depends on the light flux that occurs and the absorption capacity of semiconductors, the intrinsic concentration of semiconductor carriers, at temperature, and on several other factors. [10], [11].

![Fig. 1. (a) Basic structure of PV cells [10] and (b) Physical shape of cells and PV modules [12].](image)

The smallest part of a PV is a PV sek. These PV cells generally use Silicone material and have a minimum thickness of 0.3 mm and typically produce a voltage of 0.5 V and current of 0.1 A [13], [14]. PV cells are assembled in series, parallel or series and parallel to other PV cells will generate PV modules. PV cells are arranged in series, then the voltage will increase in proportion to the number of cells. While cells are arranged in parallel will increase the output flow. Series-connected and parallel solar cells increase voltage and increase their output flow[15]. PV modules are generally arranged in series over PV cells. So in this condition the characteristics of the cells are assumed to be identical. Therefore the PV module is considered a single cell comparable to the number of cells connected to the series[16].

PV characteristics are generally depicted on the I-V curve and or kuva P-V, as shown by figure 2 from this curve we will get some basic parameters of a PV module/panel namely I_{sc}, V_{oc}, I_{mp}, V_{mp} and P_{mp}. I_{sc} is a short circuit current measured in the MODULE/PV panel terminal, where in this condition, the voltage is 0 V. V_{oc} is an open hyphen voltage condition where the current is 0 V. I_{mp}, V_{mp} and P_{mp} respectively are the maximum current, voltage and power generated by pv
modules/panels. The \( I_{mp} \) will always be smaller than \( I_{sc} \) so \( V_{mp} \) will always be smaller than \( V_{oc} \). These parameters are generally listed in the pv module/panel data sheet.

![I-V and P-V curves of a PV module](image)

**Figure 2.** I-V and P-V curves of a PV module [3].

A PV simply (equivalent) consists of a current source, one or two Diodes (D), with or without internal series resistance\( (R_s) \) and parallel resistance \( (R_p) \). Based on literature [5] The equivalent series of a PV there are 3 types namely model one Diode with series obstacles, one Diode model with series and parallel obstacles as well as two Diode models with series and parallel obstacles. The models are presented in figure. 3.

\( R_s \) the equivalent circuits each regenerate contact resistance from the metal base with the p semiconductor layer, the resistance of the p and n bodies, the contact resistance of the nth layer with the upper metal grid, and the lattice resistance. While \( R_p \) mainly due to the leakage of p-n junction current and depending on pv cell fabrication method. The \( R_p \) generally high and some previous studies ignored this resistance to simplify the model. The \( R_s \) very low, and sometimes these parameters are ignored as well [10]. Diode represents the effect (loss) of electron current recombination. Model 1 Diode assumed that there was no effect of recombination while model 2 Diode took into account those effects.

![PV equivalent series models](image)

**Figure 3.** PV equivalent series PV equivalent (a). ideal, (b). one Diode with parallel obstacles, (c). one Diode with series and parallel obstacles and (d). one Diode with series and parallel obstacles [5].

Model one Diode with series obstacles (model 1). The equivalent series of models is presented in figure. 3a. In this model there is a series resistance \( (R_p) \). The mathematical model is written like [3]:

\[
I = I_{ph} - I_0 \left( \frac{\exp \left( \frac{V + IR_s}{aV_T} \right) - 1}{i_D} \right)
\]

With:

\[V_T = \frac{N_a k T_{STC}}{q}\]

\( I_{ph} \) is a photon current (\( A \)) provided by the [4], [10]:

1
\[ I_{ph} = \left[ I_{ph,STC} + K_i (T - T_{STC}) \right] \frac{G}{G_{STC}} \]

\( I_0 \) is a diode saturation current (A) obtained by [10]:
\[ I_0 = \frac{\left[ I_{oc,STC} + (K_i \Delta T) \right]}{\exp\left[ (V_{oc,STC} + (K_V \Delta T))/aV_T \right]} - 1 \]

Model one Diode with series and parallel obstacles (model 2). The equivalent range of this model is presented in figure 3b. This model is almost the same as the previous model there is only additional parallel resistance (\( R_p \)). The mathematical model is given as:
\[ I = I_{ph} - I_0 \left[ \exp\left( \frac{V + IR_s}{aV_T} \right) - 1 - \frac{V + IR_s}{R_p} \right] \]

Two Diode models with series and parallel barriers (model 3) This model bears a resemblance to the Model 1 Diode but there are additional 1 Diodes installed parallel as in figure 3c. The mathematical model is expressed as:
\[ I = I_{ph} - I_0 \left[ \exp\left( \frac{V + IR_s}{V_T} \right) + \exp\left( \frac{V + IR_s}{(p-1)V_T} \right) + 2 - \frac{V + IR_s}{R_p} \right] \]

\( I_0 \) this model is
\[ I_0 = \frac{\left[ I_{oc,STC} + (K_i \Delta T) \right]}{\exp\left[ (V_{oc,STC} + (K_V \Delta T))/\left( (a_1 + a_2)/p \right)V_T \right]} - 1 \]

3. Methodology
Pv to be performed performance test is mono-crystalline type where data from PV type to perform simulation is based on data sheet. In this study the software used to model PV and simulate the model is MATLAB / SIMULINK. Parameters to be measured later are the I-V and P-V curves in standard solar temperature and radiation conditions, temperature variations, variations in solar radiation, as well as the influence of Diode ideal factors, series and parallel barriers. Pv to be performed performance test is mono-crystalline type where data from PV type to perform simulation is based on data sheet. In this study the software used to model PV and simulate the model is MATLAB / SIMULINK. Parameters to be measured later are the I-V and P-V curves in standard solar temperature and radiation conditions, temperature variations, variations in solar radiation, as well as the influence of Diode ideal factors, series and parallel barriers. The most basic and important thing to look for in modeling and describing the characteristics of the I-V PV curve is the value of the \( R_s \) and \( R_{sh} \) parameters (the second stage of the research procedure). Both values are unknown and are not listed also in the data sheet. The value of these parameters depends on the experiment data. Some studies of these parameters are calculated with mathematical equations there are also iterations. Look for \( R_s \) and \( R_{sh} \) with the iteration method as has been done by[10] is by matching the maximum power point (\( P_{mpp} \)) i.e. of the model's I-V curve \( (P_{mpp}) \) with the experimental maximum power of the data sheet \( (P_{mpp_e}) \). In the process of iterating the \( R_p \) value while looking for the \( R_s \) value to the \( P_{mpp} = P_{mpp_e} \). Similarly, in this study, to look for both parameters using algorithms from[10]. While the selection of \( \alpha \) value is based on [17]. The stages or procedures performed in this study are presented in figure 4.
### Table 1. Mathematical model parameters of various PV equivalent sets.

| Symbol | Description | Unit | Value |
|--------|-------------|------|-------|
| $q$    | Electron charge | C    | $1.6 \times 10^{-19}$ |
| $k$    | Boltzmann Constants | J/K | $1.38 \times 10^{-23}$ |
| $a$    | Diode ideal factor |     |       |
| $N_s$  | Number of connected solar cells series |     |       |
| $K_t$  | Short-circuit temperature coefficient in standard conditions ($T = 298 \, ^\circ\text{K}$ and $G = 1000 \, \text{W/m}^2$) | A/K |       |
| $T$    | Operating temperature | K    | 298   |
| $T_{STC}$ | Standard temperature | K    | 298   |
| $G$    | Solar radiation | W/m² | 1000  |
| $ \theta_{STC}$ | Radiation matahari standar |       |       |
| $V_{oc,STC}$ | Open hyphen voltage ($T = 298 \, ^\circ\text{K}$ and $G = 1000 \, \text{W/m}^2$) | V    |       |
| $I_{sc,STC}$ | Short circuit current ($T = 298 \, ^\circ\text{K}$ and $G = 1000 \, \text{W/m}^2$) | A    |       |
| $K_v$  | Connect voltage temperature coefficient opens under standard conditions | %/°C |       |
| $K_t$  | Short hyphen voltage temperature coefficient under standard conditions | %/°C |       |
| $R_s$  | Prisoner series | Ω    |       |
| $R_p$  | Parallel prisoners | Ω    |       |
| $a$    | Diode ideal factor for models 1 and 2 |       |       |
| $a_1$, $a_2$ | Diode ideal factor for model 3 |       | $1 \leq a \leq 1.5$ |
| $p$    | Replacement variables $c_1^2$ and $c_2^2$ on model 3 Diode |       |       |

The PV module/panel used in this study is the CSP P6 250P one of the products of Canadian Solar. The specifications of this PV module are presented in table 2.

### Table 2. CSP P6 250P PV Module Specifications Under Standard Conditions.

| Parameters | Value | Unit |
|------------|-------|------|
| Shortcircuittcurrent ($I_{sc}$) | 8.74  | A    |
| Openhyphenvoltage ($V_{oc}$)    | 37.5  | V    |
| Maximumcurrent ($I_{mp}$)       | 8.22  | A    |
| Maximumvoltage ($V_{mp}$)       | 30.4  | V    |
| Connectvoltagetemperaturecoefficientopensunderstandardconditi ons ($K_v$) | -0.35 | %/°C |
| Shorthyphenvoltagetemperaturecoefficientunderstandardconditi ons ($K_t$) | 0.06  | %/°C |
| Numberofconnectedcellseries ($N_s$) | 60    |      |
| Polly/Multi-crystalline PV modules | | |

As explained in the previous section that pv module models will be modeled on matlab softwate using simulink features. This modeling is based on, and respectively for model 1, model 2 and model 3. For model 1, the value a used is 1.3 with $R_s = 0.298595 \, \Omega$, while for model 2 $R_s = 0.26 \, \Omega$, $R_{sh} = 312.156505 \, \Omega$ and model 3 $R_s = 176.4 \, \Omega$, $R_{sh} = 312.156505$. 


Figure 4. Research Procedures.

Model validation is done by comparing the parameters of the simulation results obtained with data sheets from pv modules that are used as material for simulation. The parameters in question are $I_{sc}$, $V_{oc}$, $I_{mp}$ dan $V_{mp}$. Comparison of simulation results with data sheets presented in table 3 value $I_{sc}$ and $V_{oc}$ obtained from the simulated I-V curve while $I_{mp}$, dan $V_{mp}$ obtained by using the following scripts:

\[
\text{pmax} = \max(\text{VIPpv.signals.values(:,3)}); \\
\text{vrange} = \max(\text{VIPpv.signals.values(:,1)}); \\
\text{irange} = \max(\text{VIPpv.signals.values(:,2)}); \\
[\text{tf, index}] = \text{ismember(pmax, VIPpv.signals.values(:,3))};
\]

| Parameters | Data sheet | Simulation Model | Error (%) |
|------------|------------|------------------|-----------|
| $I_{sc}$ (A) | 8.87 | 8.87 | 8.862 | 8.863 | 0 | 0.09 | 0.08 |
| $V_{oc}$ (V) | 37.2 | 37.2 | 37.175 | 37.13 | 0 | 0.07 | 0.19 |
| $I_{mp}$ (V) | 8.3 | 8.373 | 8.289 | 8.308 | 0.88 | 0.13 | 0.10 |
| $V_{mp}$ (V) | 30.1 | 29.855 | 30.09 | 30.16 | 0.81 | 0.03 | 0.20 |

Based on the comparison results presented in table 3 above it can be seen that the model that has been created simulation results is very close to the value stated in the PV module sheet data. Even under certain conditions the error is 0% for the value of the $I_{sc}$ and $V_{oc}$ on model 1. While the highest error value of the simulation result is 0.88%. This condition describes that the model that has been created has a high degree of accuracy.
4. Results and analysis
The simulated V-I and P-V curve results of 3 PV models can be seen in figure 5 based on the image it can be seen that the three simulated PV models have identical curves. This curve is created on the m file, where voltage, current and power data are obtained from the results of the model simulation. This is done in order to unite 3 PV module models in one curve and it is easier to add captions to curves that cannot be done in simulink mode by using the XY graph.

![Figure 5. curve I-V of various models under standard conditions.](image)

The performance characteristics of PV modules under different solar radiation conditions are presented in Figure 6(a) for mono-crystalline and figure 7(a) types. In higher solar radiation conditions, the \( I_{sc} \) and \( V_{oc} \) will be higher. The \( I_{sc} \) will decrease drastically with the decrease in solar radiation, but not with \( V_{oc} \). The value of \( V_{oc} \) will experience a small decrease in the decrease in solar radiation. The interesting thing about figure 6(b) is the performance characteristics of PV modules with varying temperatures that overwrite the surface of pv modules. Based on both images it can be seen that a rise in temperature from the standard temperature (25 °C) will cause a \( I_{sc} \) increase but cause a decrease \( V_{oc} \). While a decrease in temperature from the standard temperature will cause a decrease in \( I_{sc} \) but cause a \( V_{oc} \) increase.

The effect of the ideal factor value of a diode on the performance characteristics of pv modules is presented at figure 8(a). Based on the image it can be seen that a value will cause the maximum power increase (\( P_m \)). However, it does not affect \( I_{sc} \) and \( V_{oc} \). \( R_s \) values on models 1, 2 and 3 will affect \( P_m \) produced by PV modules. Where the greater the value of \( R_s \) will cause a decrease in the \( P_m \), but does not affect the value of \( I_{sc} \) and \( V_{oc} \). This is inversely proportional to the influence of the \( R_p \) value, where the increase in the value of \( R_p \) will causes the increase in \( P_m \). Similar to the influence of \( R_s \), the increase in the value of \( R_p \) does not affect the value of \( I_{sc} \) and \( V_{oc} \).
PV has been done and shows good results based on validation. From the simulation results obtained model 3, it has better performance compared to other models. This can be seen from the value of the $I_{mp}$ and $V_{mp}$ has a smaller error. Variations in solar radiation received by pv modules will cause changes in $I_{sc}$ but not the case with changes in the $V_{oc}$. This phenomenon is in contrast to temperature changes, where temperature changes will cause changes in $V_{oc}$ significant damage. Ideal diode factor ($a$) will cause maximum power to rise ($P_{m}$), but does not affect the value of the $I_{sc}$ dan $V_{oc}$. Especially for model 3 p value as a substitute factor $a$ cause the rise of $P_{m}$ dan $V_{oc}$. The $R_s$ will affect the $P_{m}$ inversly inversely increal $R_s$ and does not affect the value of $I_{sc}$ and $V_{oc}$. While $R_p$ has the opposite effect to $R_s$, where the increase in the value of $R_p$ while causes an increase in $P_{m}$. But it has the same effect on $I_{sc}$ and $V_{oc}$.

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References

[1] R. Chenni, M. Makhlouf, T. Kerbache, and A. Bouzid, “A detailed modeling method for photovoltaic cells,” *Energy*, vol. 32, no. 9, pp. 1724–1730, Sep. 2007.

[2] K. Ishaque and Z. Salam, “An improved modeling method to determine the model parameters of photovoltaic (PV) modules using differential evolution (DE),” *Sol. Energy*, vol. 85, no. 9, pp. 2349–2359, Sep. 2011.

[3] K. Ishaque, Z. Salam, and H. Taheri, “Simple, fast and accurate two-diode model for photovoltaic modules,” *Sol. Energy Mater. Sol. Cells*, vol. 95, no. 2, pp. 586–594, Feb. 2011.

[4] E. Saloux, A. Teyssedou, and M. Sorin, “Explicit model of photovoltaic panels to determine voltages and currents at the maximum power point,” *Sol. Energy*, vol. 85, no. 5, pp. 713–722, May 2011.

[5] T. Ma, H. Yang, L. Lu, and J. Peng, “An Optimization Sizing Model for Solar Photovoltaic Power Generation System with Pumped Storage,” *Energy Procedia*, vol. 61, pp. 5–8, 2014.

[6] P. T. Le, H.-L. Tsai, and T. H. Lam, “A wireless visualization monitoring, evaluation system for commercial photovoltaic modules solely in MATLAB/Simulink environment,” *Sol. Energy*, vol. 140, pp. 1–11, Dec. 2016.

[7] Krismadinata, N. A. Rahim, H. W. Ping, and J. Selvaraj, “Photovoltaic Module Modeling using Simulink/Matlab,” *Procedia Environ. Sci.*, vol. 17, pp. 537–546, Jan. 2013.

[8] I. Syarif, A. N. Putri, M. A. H. Sirad, and M. B. Nappu, “Frequency Stability of Hybrid Photovoltaic and Diesel Solar Power Plants Using the Resilient Back Propagation Method,” *J. Phys. Conf. Ser.*, 2020.

[9] S. N. Hutagalung, “Pemelajaran Fisika Dasar dan Elektronika Dasar Menggunakan Aplikasi Matlab Metode Simulink,” *J. Sci. Soc. Res.*, vol. 1, no. 1, pp. 30–35, 2018.

[10] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays,” *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, May 2009.

[11] E. A. Hakim, T. Al Ghufran, M. Effendy, and N. Setyawan, “MPPT Menggunakan Algoritme Particle Swarm Optimization dan Artificial Bee Colony,” *J. Nas. Tek. Elektro dan Teknol. Inf.*, vol. 9, no. 2, pp. 218–224, May 2020.

[12] University of Central Florida, “Cells, Modules, & Array,” *University of Central Florida Website*, 2020.

[13] R. Foster, M. Ghassemi, and A. Cota, “Solar Energy,” in *Renewable Energy and The Environment*, M. Ghassemi, Ed., CRC Press, 2009.

[14] S. R. Wenham, M. A. Green, M. E. Watt, R. Corkish, and A. Sproul, *Applied Photovoltaics*, 3rd ed. London, England: Routledge, 2013.

[15] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Modeling and circuit-based simulation of photovoltaic arrays,” in *2009 Brazilian Power Electronics Conference*, 2009, pp. 1244–1254.

[16] N. Ayub Windarko, M. Nizar Habibi, M. Ari Bagus Nugroho, and E. Prasetyono, “Simulator Panel Surya Ekonomis untuk Pengujian MPPT pada Kondisi Berbayang Sebagian (Low Cost PV Photovoltaic Simulator for MPPT Testing under Partial Shading),” *J. Nas. Tek. Elektro dan Teknol. Inf.*, vol. 9, no. 1, pp. 110–115, Feb. 2020.

[17] H. A. B. Siddique, P. Xu, and R. W. De Doncker, “Parameter extraction algorithm for one-diode model of PV panels based on datasheet values,” in *2013 International Conference on Clean Electrical Power (ICCEP)*, 2013, pp. 7–13.