Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Environmental Sciences 17 (2013) 537 – 546

Procedia
Environmental Sciences

The 3rd International Conference on Sustainable Future for Human Security
SUSTAIN 2012

# Photovoltaic module modeling using simulink/matlab

Krismadinata[a]*, Nasrudin Abd. Rahim[a] Hew Wooi Ping[a], Jeyraj Selvaraj[a]

[a]*University of Malaya Power Energy Dedicated Advanced Centre (UMPEDAC)*
*Level 4 Wisma R&D University of Malaya Kuala Lumpur 59990 Malaysia*

**Abstract**

This paper describes a method of modeling and simulation photovoltaic (PV) module that implemented in Simulink/Matlab. It is necessary to define a circuit-based simulation model for a PV cell in order to allow the interaction with a power converter. Characteristics of PV cells that are affected by irradiation and temperature are modeled by a circuit model. A simplified PV equivalent circuit with a diode equivalent is employed as model. The simulation results are compared with difference types of PV module datasheets. Its results indicated that the created simulation blocks in Simulink/matlab are similar to actual PV modules, compatible to different types of PV module and user-friendly


Selection and peer-review under responsibility of SUSTAIN conference's committee and supported by Kyoto University; (OPIR), (GCOE-ES), (GCOE-HSE), (CSEAS), (RISH), (GCOE-ARS) and (GSS) as co-hosts.

*Keywords*: modeling; PV module; PV characteristic; simulink/matlab

* *E-mail address*: krismadinata@um.edu.my


Selection and peer-review under responsibility of SUSTAIN conference's committee and supported by Kyoto University; (OPIR), (GCOE-ES), (GCOE-HSE), (CSEAS), (RISH), (GCOE-ARS) and (GSS) as co-hosts.
doi:10.1016/j.proenv.2013.02.069

## 1. Introduction

Due to reserve of fossil fuel dwindling and the global warming effect looming large, alternative energies become popular. The most attention of alternative energies is solar energy. There are two types of technology that employed solar energy, namely solar thermal and solar cell. A PV cell (solar cell) converts the sunlight into the electrical energy by the photovoltaic effect. Energy from PV modules offers several advantages, such as, requirement of little maintenance and no environmental pollution. Recently, PV arrays are used in many applications, such as, battery chargers, solar powered water pumping systems, grid connected PV systems, solar hybrid vehicles and satellite power systems.

PV module represents the fundamental power conversion unit of a PV generator system. The output characteristic of PV module depends on the solar insulation and the cell temperature. Since PV module has nonlinear characteristics, it is necessary to model it for the design and simulation of maximum power point tracking (MPPT) for PV system applications [1].

A PV module typically consists of a number of PV cells in series. The conventional technique to model a PV cell is to study the p-n junction physics [2]. A PV cell has a non-linear voltage-current (*V-I*) characteristic which can be modeled using current sources, diode(s) and resistors. Single-diode and double-diode models are widely used to simulate PV characteristics. The single-diode model emulates the PV characteristics fairly and accurately. The manufacturer provides information about the electrical characteristics of PV by specifying certain points in its *V-I* characteristics which are called remarkable points [3].

In this paper, a simplified PV equivalent circuit with a diode equivalent as model is proposed. The main contribution of this work is the implementation of a generalized PV model in the form of masked block which has a user-friendly icon and dialog in the same way of Matlab/Simulink block libraries.

## 2. Mathematical model for a photovoltaic cell

Fig. 1(a)-(b) are models of the most commonly-used PV cell: a current source parallel with one or two diodes. A single-diode model [4-6] has four components: photo-current source, diode parallel to source, series of resistor $R_s$, and shunt resistor $R_{sh}$. Fig.1(b) is a two-diode model: [7-9] the extra diode is for better curve-fitting.

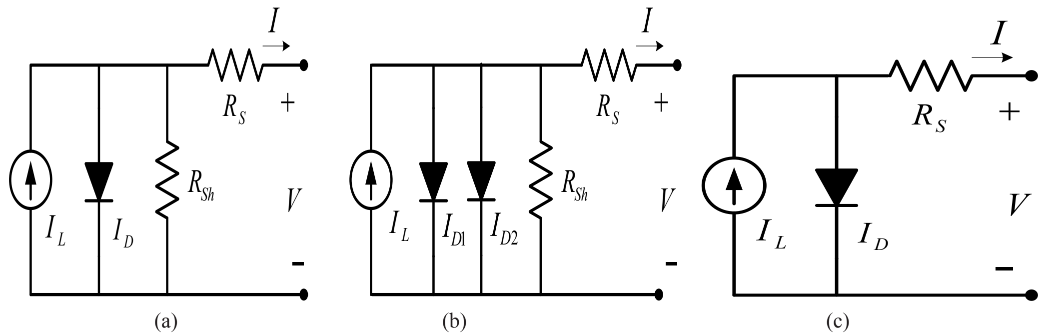


Fig. 1: PV-cell equivalent-circuit models: (a) single-diode model, (b) two-diode model (c) Simplified-PV-equivalent circuit

The shunt resistance $R_{sh}$ is large, so it usually can be neglected [8]. Fig. 1(a-b)'s four-parameter models can, thus, be simplified into Fig. 1c, the simplified equivalent-circuit model of this study.

The output voltage $V$ and the load current $I$ relate as:

$$I = I_L - I_D = I_L - I_0\left[\exp\left(\frac{V + IR_s}{\alpha}\right) - 1\right] \quad (1)$$

where $I_L$ = light current (A);
$I_0$ = saturation current (A);
$I$ = load current (A);
$V$ = output voltage (V);
$R_S$ = series resistance (Ω);
α = thermal voltage timing completion factor (V).

Four parameters ($I_L$, $I_0$, $R_S$, and α) must be determined to obtain the *I-V* relationship (the reason the model is called a four-parameter model). Fig. 1c's equivalent circuit and Equation (1) mask the complexity of the actual model, for the four parameters are functions of temperature, load current and/or solar irradiance. Procedures for determining the four parameters are given herewith.

Light Current $I_L$; [10-12], states that $I_L$ can be calculated as:

$$I_L = \frac{\phi}{\phi_{ref}}\left[I_{L,ref} + \mu_{I,SC}\left(T_C - T_{C,ref}\right)\right] \quad (2)$$

where $\phi$ = irradiance (W/m$^2$),
$\phi_{ref}$ = reference irradiance (1000 W/m$^2$ is used in this study),
$I_{L,ref}$ = light current at the reference condition (1000W/m$^2$ and 25°C),
$T_c$ = PV cell temperature (°C),
$T_{c,ref}$= reference temperature (25 °C is used in this study),
$\mu_{I,SC}$ = temperature coefficient of the short-circuit current (A/°C);
Both $I_{L,ref}$ and $\mu_{I,SC}$ are available on manufacturer datasheet [11].
Saturation Current $I_0$; this can be expressed in terms of its value at reference conditions [10-12]:

$$I_0 = I_{0,ref}\left(\frac{T_{C,ref} + 273}{T_C + 273}\right)^3 \exp\left[\frac{e_{gap}N_S}{q\alpha_{ref}}\left(1 - \frac{T_{C,ref} + 273}{T_C + 273}\right)\right] \quad (3)$$

where $I_{0,ref}$= saturation current (A) at reference conditions,
$e_{gap}$ = band gap of the material (1.17 eV for Si materials),
$N_s$ = number of cells in series of a PV module,
$q$ = charge of an electron (1.60217733×10$^{-19}$ C),
$\alpha_{ref}$= the value of α at reference conditions.

$I_{0,ref}$ can be calculated as:
$$I_{0,ref} = I_{L,ref}\exp\left(-\frac{V_{oc,ref}}{\alpha_{ref}}\right) \quad (4)$$

where $V_{oc,ref}$ = the reference-condition open-circuit voltage (V) of the PV module; its value is manufacturer-provided.
In [10-12] state that $\alpha_{ref}$ can be calculated from

$$\alpha_{ref} = \frac{2V_{mp,ref} - V_{oc,ref}}{\dfrac{I_{sc,ref}}{I_{sc,ref} - I_{mp,ref}} + \ln\left(1 - \dfrac{I_{mp,ref}}{I_{sc,ref}}\right)} \tag{5}$$

where $V_{mp,ref}$ = maximum power point voltage (V) at reference conditions,
$I_{mp,ref}$ = maximum power point current (A) at reference conditions,
$I_{sc,ref}$= short-circuit current (A) at reference conditions.

α is a function of temperature, expressed as:

$$\alpha = \frac{T_C + 273}{T_{C,ref} + 273}\alpha_{ref} \tag{6}$$

Series resistance $R_s$ is manufacturer-provided; but, if not, this equation can be used to estimate it [11, 12]:

$$R_S = \frac{\alpha_{ref}\ln\left(1 - \dfrac{I_{mp,ref}}{I_{SC,ref}}\right) + V_{OC,ref} - V_{mp,ref}}{I_{mp,ref}} \tag{7}$$

Fig. 2 shows the *I-V* operating characteristics of a solar cell. A PV array comprises individual PV cells connected into a unit of suitable power rating. Its characteristics are determinable by multiplying the voltage of an individual cell by the number of cells connected in series and multiplying the current by the number of cells connected in parallel. Three important operating points are open-circuit voltage, short-circuit current and Maximum Power Point (MPP).

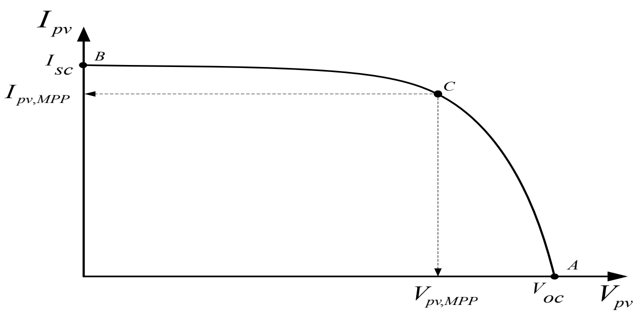


Fig. 2: PV-cell operating point

Voltage at operating-point-A in Fig. 2 is the open-circuit voltage. Fig. 3 shows an open circuit with shunt current $I_{sh}$ neglected. Equations (8) and (9) represent.

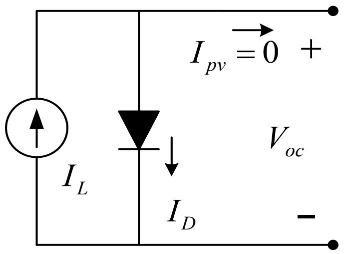


Fig. 3: Equivalent circuit, open-circuit condition

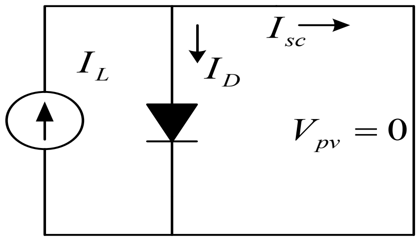


Fig. 4: Equivalent circuit, short-circuit condition

$$I_L - I_0\left[\exp\left(\frac{V_{OC}}{\alpha}\right) - 1\right] = 0 \tag{8}$$

$$V_{OC} = \alpha \ln\left(\frac{I_L + I_0}{I_0}\right) \tag{9}$$

Equation (10) gives the short-circuit current. Fig. 4 shows it and the current at operating point B, neglecting series resistance $R_s$.

$$I_{SC} = I_L \tag{10}$$

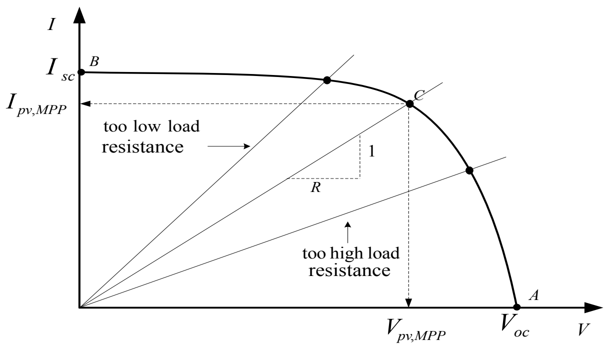


Fig. 5: Intersection of the *I-V* characteristic and the load characteristic curve

The operating point of a PV array under constant irradiance and cell temperature is the intersection point of the *I-V* characteristics and the load characteristics; see Fig. 5. A straight line with gradient $M=1/R= I_{Load}/V_{Load}$ represents the load characteristic. The system's operating point moves along the PV panel's *I-V* characteristic curve, from B to A, as load resistance increases from zero to infinity. The MPP is at C, where the area (equivalent to output power) under the *I-V* characteristic curve is maxima. For too-high load resistances, the operating points go into the CA region. For too-low load resistances, the operating points go into the CB region. MPP can, thus, be obtained by matching load resistance to PV array characteristics [13].

## 2.1. Cell characteristics

PV-cell characteristics depend on insulation and temperature; see equations (1) to (6). This becomes apparent when evaluating equation (1) for selected values of temperature and irradiance and plotting the results on an *I-V* graph (Fig. 6). Fig. 6(a) shows array output current *I* influenced by change in insulation *S*, whereas output voltage *V* is almost constant. Contrarily, for temperature that changes, voltage seems to vary widely, but current is unchanged; see Fig. 6(b).

The *P-V* characteristics of a PV cell array can be obtained from its *I-V* characteristics. Fig. 7 shows the output-power relation $P=V.\ I$. These figures prove how the dependence of output current *I* and output voltage *V* on temperature and insulation translate into dependence of output power on *V* and *I*.

Fig. 7 also confirms the behaviour expected from a solar-energy-converting device: its output power reduces with decreased irradiation. The reduced-power effect from increased panel-temperature is not immediately obvious, but is concordant with temperature's significant effect on open-circuit voltage $V_{oc}$.

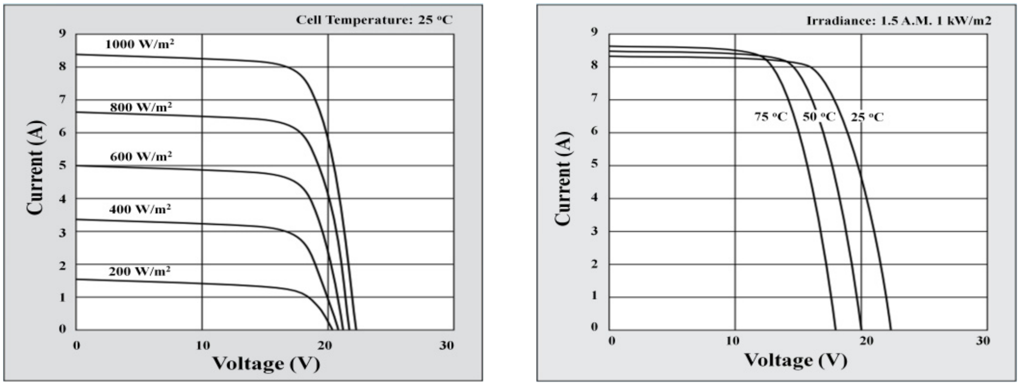


Fig. 6: *I-V* characteristics of a PV cell array for KD135GX-LPU [14]
(a) for various values of irradiance *S* at $25^0$C (b) for various values of temperature *T* at 1000W/m2

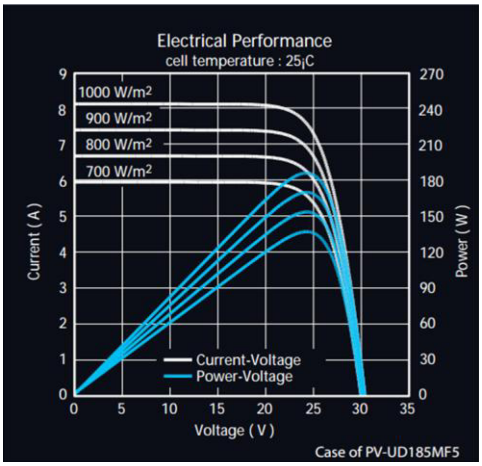


Fig.7: Characteristics of Mitsubishi 185W module PV-UD185MF5 (source: Mitsubishi datasheet)

### 2.2. Shading

PV modules are ultra-sensitive to shade. Unlike solar-thermal panels (which are tolerant of some shade), most PV modules cannot be shaded by even a leafless tree's branch. Shadings can be soft-sourced or hard-sourced. Tree branch, roof vent, chimney and other such distant shadings (these are soft sources) diffuse/disperse the shadow. Soft sources significantly reduce the light from reaching a module's cells. Hard sources stop light altogether from reaching a cell. A blanket, a tree branch and bird droppings are hard sources - they are on the glass. Hard shading of even one cell halves module's non-shaded voltage. Adequate hard shading of adequate cells not only stops module from converting energy; it drains the entire system's energy. Short-circuit current of the shaded cell decreases by 75%; such drastic increase also occurs in the PV series' potential energy [15]. What happens is depended on how many cells there are in the series and on the loading device. In the worst case, the shaded cell is forced to reverse voltage, and starts dissipating – rather than producing – power. It heats up. At temperatures above approx. $130^0$C, its function starts degenerating irretrievably.

## 3. Simulations of *I-V* curves and *P-V* curves

The electro-physical output rating of PV modules are given at specific conditions. These conditions are called Standard Test Conditions (STC) which is defined as follows:

Table 1: Standard test condition

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Irradiance at normal incidence | G | 1000 | $Wm^2$ |
| Cell temperature | T | 25 | $^0$C |
| Solar spectrum | AM | 1.5 | - |

The STC relates to the IEC 60904 standards, short-circuit current $I_{sc}$, open-circuit voltage $V_{oc}$ and maximum-point power ($P_{mpp}$) that are specified for PV modules to ±10% tolerance. Realistically, these conditions occur very rarely; however, if the sun shines with the specified intensity, then, cell temperature will be higher than 25°C.

*I-V* curves and *P-V* curves were simulated for various irradiances and temperatures by using MATLAB. The PV-AE125MF5N module was chosen as it is one of the types to be used in the experimental prototype. Table 2 indicates the PV module's characteristics.

Table 2: Characteristics of the PV Module

| Specifications | Specifications PV module from datasheet Mitsubishi PV-AE125MF5N<br>% | Value |
|---|---|---|
| Open circuit voltage ($V_{oc}$) | | 21.8V |
| Short circuit current ($I_{sc}$) | | 7.90A |
| Maximum power voltage ($V_{mpp}$) | | 17.3V |
| Maximum power current ($I_{mpp}$) | | 7.23A |
| Maximum power rating ($P_{max}$) | | 125W |
| Maximum system voltage | | 600V |
| Temperature coefficient _ $I_{sc}$ | 0.08 | 0.001904 |
| Temperature coefficient _ $V_{oc}$ | | -0.28 |

| | |
|---|---|
| Temperature coefficient _$P_{mpp}$ | -0.23 |
| Normal operating cell temperature (NOCT) | 75 |
| Number of cells | 36 |

In Fig. 8, it shows PV module that was modelled and simulated in Matlab/Simulink for variable irradiance and constant temperature 25 $^0$C. This model comprised the blocks that were developed from equation (1) to (10). While in Fig. 9 it depicted PV modelled module in Matlab/Simulink on the effect of the temperature.

Fig. 10 shows the module's *I-V* curved for various irradiances and constant temperatures. The irradiance ranged from 200W/m$^2$ to 1100W/m$^2$ while temperature was maintained at 25 $^0$C. As the irradiance increased, the current increased. Voltage, on the other hand, remained relatively constant throughout the irradiance range. Fig. 11 shows the module's *P-V* curved for various irradiances and 25 $^0$C constant temperatures.

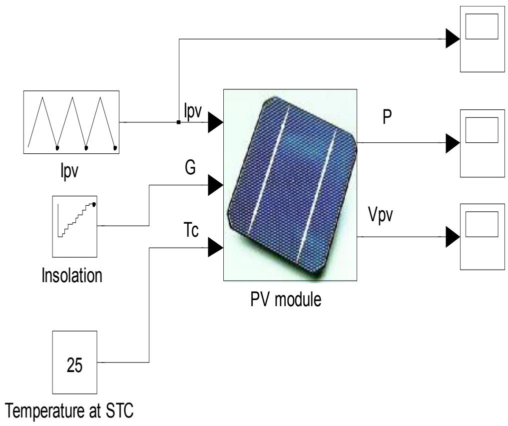


Fig. 8: PV module model for variable irradiance and constant temperature

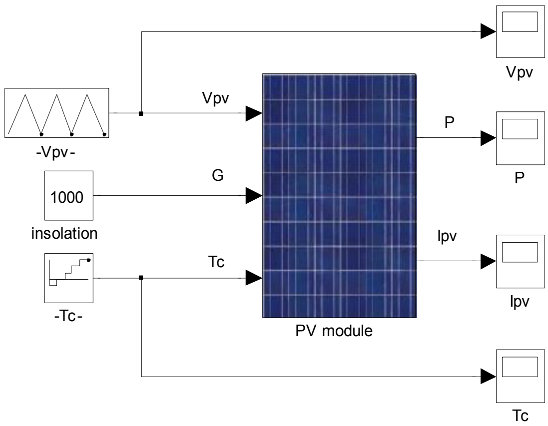


Fig 9: PV module model for variable irradiance and constant temperature

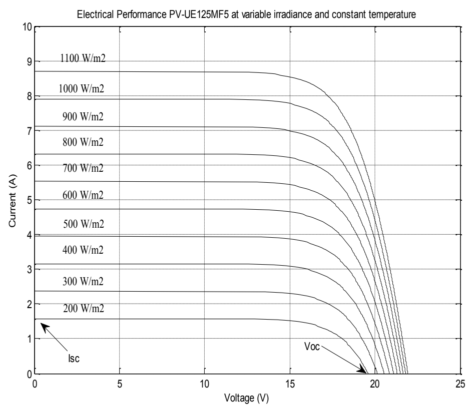


Fig. 10: Module's *I-V* curves for various irradiances and constant temperature

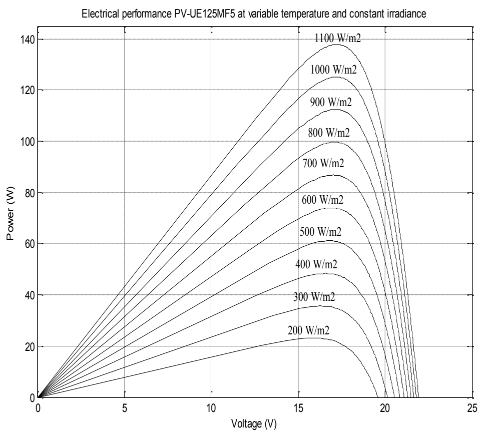


Fig 11: Module's *P-V* curves for various irradiances and constant temperature

Fig. 12 shows the module's *I-V* curved for various temperatures and 1000W/m$^2$ constant irradiance. The temperature ranged from -25°C to 75°C. The panel's performance was noted to be best at -25°C and 1000W/m$^2$ irradiance. Fig. 13 shows the *P-V* curved for various module temperatures at 1000W/m$^2$ constant irradiance.

From the two Fig. 12 and 13, it was noted that the lower the temperature, the higher the maximum power is and the larger the open circuit voltage is. On the other hand, a lower temperature gave a slightly lower short circuit current.

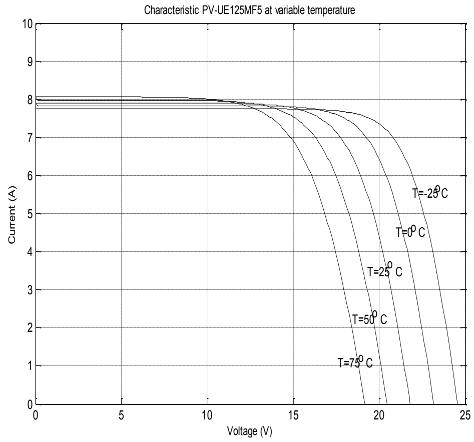


Fig. 12: Module's *I-V* curves for various temperatures and constant irradiance

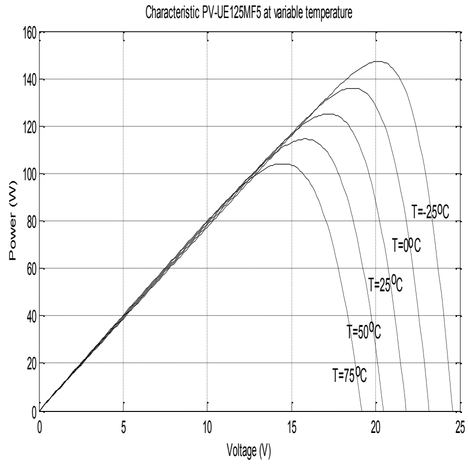


Fig 13: Module's *P-V* curves for various module temperatures and constant irradiance

Fig. 14 shows characteristic curves of PV-AE125MF5N for various values of irradiance S at temperature 25$^0$C. This module was employed as data sample to simulate. Simulation results, especially in Fig. 10 and 11, showed that they were similar with characteristic PV-AE125MF5N from datasheet.

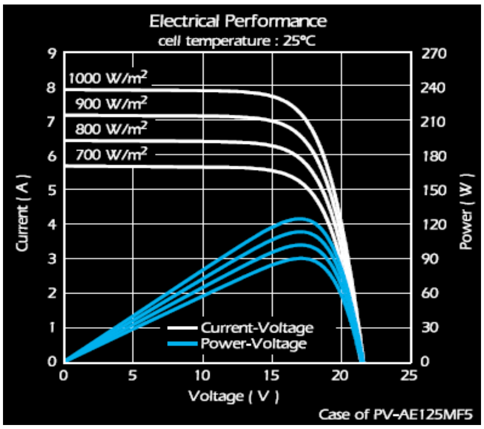


Fig. 14: Characteristic curves of PV-AE125MF5N (source: Mitsubishi datasheet)

## 4. Conclusion

An accurate PV module electrical model was presented and demonstrated in Simulink/Matlab for a typical 125W solar panel. The proposed modeling method avoided complexities involved in PV parameter identification while achieving comparable accuracy. Simulation results were verified by comparing on the experiment results of datasheet. It proved the effectiveness of the proposed modeling method. The method was easy to implement in various simulation platforms for PV power systems studies.

## References

[1] C.-S. T. Huan-Liang Tsai, and Yi-Jie Su, "Development of Generalized Photovoltaic Model Using MATLAB/SIMULINK," in *the World Congress on Engineering and Computer Science 2008*, San Francisco, USA, 2008.

[2] W. Shen, H. Choo Fook, P. Wang, C. Loh Poh, and Y. Khoo Sui, "Development of a mathematical model for solar module in photovoltaic systems," in *Industrial Electronics and Applications (ICIEA), 2011 6th IEEE Conference on*, 2011, pp. 2056-2061.

[3] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," *Power Electronics, IEEE Transactions on,* vol. 24, pp. 1198-1208, 2009.

[4] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Modeling and circuit-based simulation of photovoltaic arrays," in *Power Electronics Conference, 2009. COBEP '09. Brazilian*, 2009, pp. 1244-1254.

[5] J. Yuncong, J. A. A. Qahouq, and M. Orabi, "Matlab/Pspice hybrid simulation modeling of solar PV cell/module," in *Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE*, 2011, pp. 1244-1250.

[6] A. Chatterjee, A. Keyhani, and D. Kapoor, "Identification of Photovoltaic Source Models," *Energy Conversion, IEEE Transactions on,* vol. PP, pp. 1-7, 2011.

[7] J. A. Gow and C. D. Manning, "Development of a photovoltaic array model for use in power-electronics simulation studies," *Electric Power Applications, IEE Proceedings -,* vol. 146, pp. 193-200, 1999.

[8] X. Weidong, W. G. Dunford, and A. Capel, "A novel modeling method for photovoltaic cells," in *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, 2004, pp. 1950-1956 Vol.3.

[9] Z. Salam, K. Ishaque, and H. Taheri, "An improved two-diode photovoltaic (PV) model for PV system," in *Power Electronics, Drives and Energy Systems (PEDES) & 2010 Power India, 2010 Joint International Conference on*, 2010, pp. 1-5.

[10] Ø. Ulleberg, "Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems,," PhD dissertation, Norwegian University of Science and Technology, Trondheim,, 1998.

[11] T. U. Townsend, "Method for Estimating the Long-Term Performance of Direct-Coupled Photovoltaic Systems,," MS Thesis, University Of Wisconsin, madison, 1989.

[12] C. Wang, "Modeling and Control of Hybrid Wind/Photovoltaic/Fuel cell Distributed Generation Systems," PhD Dissertation, Montana State University, Bozeman, 2006.

[13] Y. T. Tan, "Impact on The Power System with a Large Penetration of Photovoltaic Generation," PhD Thesis, Electrical Engineering and Electronics, Umist, Manchester, 2004.

[14] Kyocera, "High Efficiency Multicrystal Photovoltaic Module KD135GX-LPU ", Kyocera, Ed., ed. Northern Arizona, 2008.

[15] B. Lindgren, "A Power Converter for Photovoltaic Applications," Licentiate of Engineering Degree, Department of Electric Power Engineering, Chalmers University of Technology Göteborg, Sweden, 2000.