A Simulink Model of Photovoltaic Modules under Varying Environmental Conditions

Innocent Nkurikiyimfura[12], Bonfils Safari[1] and Emmanuel Nshingabigwi[1]

1 Physics Department, School of Science, College of Science and Technology, University of Rwanda, Po. Box: 3900 Kigali, Rwanda
2 African Center of Excellence in Energy for Sustainable Development (ACEESD), College of Science and technology, University of Rwanda, Po. Box: 3900 Kigali, Rwanda
E-mail: inkurikiyimfura@ur.ac.rw

Abstract. In this paper, a model for predicting the effects of environmental conditions on the performance of photovoltaic panels is developed and analysed. A one-diode model taking into account effects of environmental conditions such as solar irradiance, ambient temperature and wind was developed and simulated in Simulink/Matlab environment. The accuracy of the developed model was confirmed *via* a comparison of the simulated results with the output characteristics of two polycrystalline photovoltaic (PV) modules from different manufacturers. Effects of various environmental parameters on the cell temperature and output characteristics of PV modules were analysed using the developed model. The results revealed that environmental condition variations have significant effects on the electrical performances of PV modules and should be taken into consideration in PV system design. The developed model could also be useful in the design of optimum cooling systems for photovoltaic/thermal (PV/T) systems since it takes into consideration the cooling effects of the wind.

1. Introduction

Photovoltaic (PV) solar energy conversion has received continuous attentions for decades as a clean, inexhaustible, reliable and cheap renewable energy technology [1–3]. In a PV system, solar energy is directly converted into direct current (DC) electricity on the smallest units known as PV cells. For higher output voltages, PV cells are generally grouped in series and/or parallel. On the surface of a PV solar cell, incident solar energy is converted into electricity via the so-called photovoltaic effect. The operating temperature and thus the overall performances of any PV solar module are generally affected by environmental conditions such as solar irradiance intensity, wind speed and direction, ambient temperature, etc. [4–6]. While higher ambient temperature and the solar irradiance have detrimental effects on the overall performance of solar modules, high speed wind could lower the cell temperature leading to an enhancement in the overall performances of the PV module. In previous studies, effects of ambient temperature and solar irradiance on the performances of solar cells/modules were extensively investigated using experimental and mathematical modelling [2,7].

Various models accounting for the ambient temperature and solar radiation have been thoroughly investigated based on the single diode [3,8,9], two-diode [10–12] and recently, three-diode [13,14] models. The developed models are generally simulated using various software programs including C-language programs, excel, Matlab, Simulink, SPICE, etc. [5,15]. Although two-diode and three-diode based models have shown more accurate results, the use of one-diode model has received more attention due to its simplicity and ease of simulation using various software packages such as

IOP Conf. Series: Earth and Environmental Science **159** (2018) 012024 doi:10.1088/1755-1315/159/1/012024

Matlab/Simulink [11]. Using one-diode models, various authors have accurately simulated effects of ambient temperature and solar radiation using Simulink [2,16]. They confirmed that the P-V and I-V characteristics of PV modules could be strongly affected by the ambient temperature and solar radiation. While increased solar radiation increases the output characteristics of the solar modules, higher temperatures have detrimental effects on them. Ayaz et al. [17] developed an improved matlab/simulink model considering the ambient conditions. The developed model was tested on various PV technologies including monocrystalline silicon, polycrystalline silicon, and thin films and the results were validated experimentally. The comparison of the simulated and experimental results under real atmospheric conditions showed good agreement for monocrystalline silicon and thin films. However, the prosed model showed lower performances for polycrystalline silicon.
Models that take into consideration the effects of environmental condition variations on the output characteristics on PV module are rare in the literature. Therefore, this work is devoted to developing a MatLab/Simulink model that could be used to analyze the combined effects of environmental conditions on the performances of PV modules. A model that accounts for wind speed, ambient temperature, and solar irradiance intensity was developed and used to analyze the output characteristics of polycrystalline PV modules.

2. Photovoltaic models

2.1. Photovoltaic cell model
A photovoltaic (PV) cell is the smallest unit of a photovoltaic module, with power output of less than 2 W at 0.5 V [4]. A PV cell is physically modelled using the equivalent circuit of Figure 1 (a) [4,8]. It consists of a photocurrent and a diode with an internal resistance connected to a parallel resistor that simulates a leakage current [4].

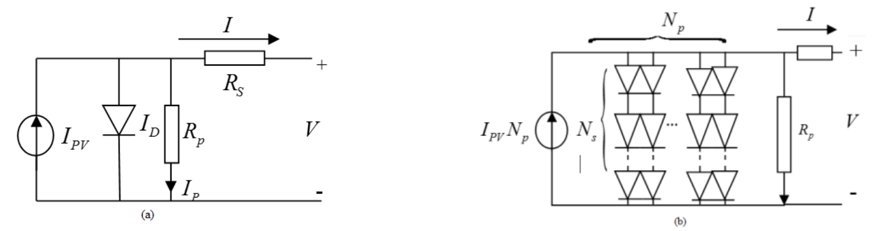

Figure 1. Physical model of (a) photovoltaic solar cell and (b) photovoltaic solar module

According to the well-known Kirchhoff's current law, the current flowing in the circuit (*I*) can be modelled by the following equation [14]:

$$I = I_{PV} - \underbrace{I_0\left[\exp\left(\frac{qV}{Ak_BT_{cell}}\right)-1\right]}_{I_D} - \underbrace{\frac{V+IR_s}{R_p}}_{I_p} \qquad (1)$$

where I_{PV} is the light-generated current also referred to as photocurrent, I_0 is the dark saturation current, T_{cell} is the cell temperature, $k_B = 1.3806503\times10^{-23}\,JK^{-1}$ represents the Boltzmann constant and $q = 1.6\times10^{-19}\,C$ is the electron charge. *V*, *A*, R_s and R_p are the voltage, ideality factor, series resistance and shunt resistance, respectively.

2.2. Photovoltaic module model
A photovoltaic module consist of an array of several PV cells electrically connected in a series-parallel configuration [4]. An equivalent circuit of a photovoltaic module is depicted in Figure 1 (b). In the circuit, PV cells are arranged in N_p parallel and N_S series branches. Similarly to the PV cell model, the current flowing generated by a PV module could be modelled as [2]

$$I = N_p I_{PH} - N_p I_0 \left[\exp\left(\frac{V + IR_s}{AV_t} \right) - 1 \right] - \frac{V + IR_s}{R_p} \tag{2}$$

where the parameter V_t, also known as thermal voltage, is calculated using the following formula

$$V_t = \frac{N_s k_B T_{cell}}{q} \tag{3}$$

In practice the shunt resistance can be set equal to infinity. Thus, last term of equation (2) can be omitted and the current equation can be written in its simplified form as follows [2,18]

$$I = N_p I_{PH} - N_p I_0 \left[\exp\left(\frac{V + IR_s}{AV_t} \right) - 1 \right] \tag{4}$$

The photocurrent is calculated as [18]

$$I_{PH} = I_{PH,STC} + K_I \left(T_{cell} - T_{STC} \right) \frac{G}{G_{STC}} \tag{5}$$

where $I_{PH,STC}$ is the photocurrent at standard testing conditions, which is approximately equal to the short circuit current (I_{sc}) and K_I is the temperature coefficient of the current which is generally provided by the PV cell manufacturers. G and G_{STC} stand for the solar insolation intensity and solar insolation intensity under standard testing conditions (i.e., T_{STC}*=298K*, *G=1000Wm*$^{-2}$, and air mass, *AM=1.5*), respectively.

The reverse saturation current is calculated as

$$I_0 = I_s \left(\frac{T_{STC}}{T_{cell}} \right)^3 \exp\left[\frac{qE_g}{Ak_B} \left(\frac{1}{T_{STC}} - \frac{1}{T_{cell}} \right) \right] \tag{6}$$

where I_s is the saturation current, T_{STC}*=298K* is the standard test temperature and E_g is the band gap of the semiconductor, which is estimated at *1.12 eV* for silicon semiconductors. The saturation current is calculated as

$$I_s = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{N_s A k T_{STC}} \right) - 1} \tag{7}$$

where I_{sc} and V_{oc} are the short circuit and open voltage, respectively.

2.3. Cell temperature under varying environmental conditions

The cell temperature is a key parameter for PV module performance evaluation. In previous studies, various models were proposed. A comprehensive review of cell temperature models and their comparison is provided in [19]. Most of the proposed models account for solar irradiance and temperature as environmental parameters. In this work, a model combining effects of solar irradiance, wind, and ambient temperature is used. On-cell temperature is conveniently modeled using the following equation for polycrystalline silicon PV cells [19,20].

$$T_{cell} = \frac{U_{PV}(v) T_a + G\left[\tau\alpha - \eta_{STC} \left(1 - \beta_{STC} T_{STC} \right) \right]}{U_{PV}(v) + \eta_{STC} \beta_{STC} G} \tag{8}$$

where G and T_a are the irradiance and ambient temperature, respectively. η_{STC} and β_{STC} are the efficiency and the temperature coefficient of maximal power under standard test conditions. The parameter $U_{PV}(v)$ is the heat exchange coefficient for the total surface of the cell. For polycrystalline silicon PV cells, $U_{PV}(v)$ is estimated using the following equation [19,20].

$$U_{PV} = 26.6 + 2.3v \tag{9}$$

where v is the wind speed.

3. Environmental conditions effects modeling and simulation

3.1. Photovoltaic module parameters

In this study, two polycrystalline silicon PV modules, i.e., KT260-6GC-A (Kyocera ltd., Japan) and ND-220(ELF) (Sharp, Sharp Energy Solution Europe, German) were used to assess the accuracy of the developed Matlab/Simulink model. The key specifications of these modules are summarized in Table 1.

Table 1. Solar modules specifications (1000Wm-2, 298 K, AM=1.5)

Characteristics	Specifications	
Type	KT260-6GC-A	ND-220(ELF)
Maximum power (P_{max})	260 Wp	220 Wp
Maximum power current (I_{mp})	8.39 A	7.54 A
Maximum power voltage (V_{mp})	31 V	29.2 V
Short circuit current (I_{SC})	9.09 A	8.2 A
Open circuit voltage (V_{OC})	38.3 V	36.5 V
Module efficiency	15.8%	13.4%
Temperature coefficient of (I_{sc})	+0.06%/K	+0.053%/^{0}C
Temperature coefficient of (V_{oc})	-0.36%/K	-0.13 %/^{0}C
Temperature coefficient of (P_{max})	-0.45%/K	-0.485% ^{0}C
TOCT	45 ^{0}C	47.5^{0}C

3.2. Matlab/simulink model building and performances analysis

A MatLab/Simulink model taking into account effects of solar irradiance intensity, ambient temperature, and wind as environmental parameters was built and used to analyze I-V and P-V characteristics of polycrystalline PV modules.

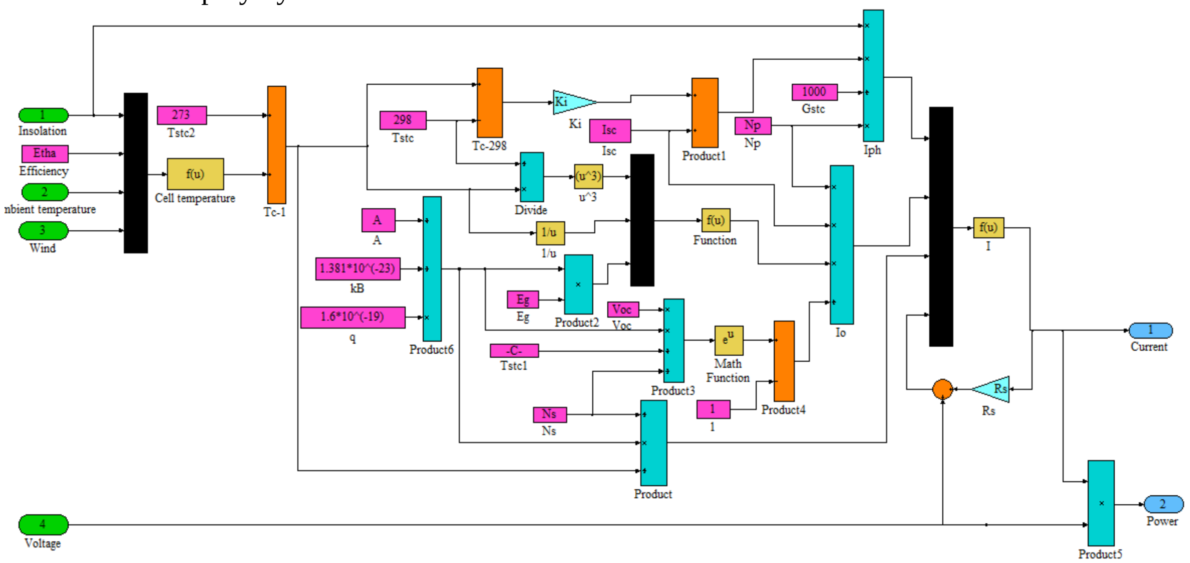

Figure 2. Simulink subsystem implementation of a PV module under varying environmental conditions

The block diagram of the developed model is shown on Figure 2. In this model, various environmental parameters including solar irradiance intensity, ambient temperature, and wind were used as input parameters (Figure 3 a). The current and power were estimated at various operating voltages which was modelled using a ramp block with 0.95 as input parameter. The cell temperature and PV models (equations 3 through 8) were modelled using appropriate simulink built-in functions and various parameters were fed into the model *via* the developed dialog box (Figure 3 b).

Performances of the developed model were assessed via a comparison of the simulated results and the I-V and P-V characteristics provided in the datasheets of two polycrystalline PV modules taken as example (**Table 1**). Figure 4 and 5 show the simulated I-V and P-V output characteristics of the two modules.

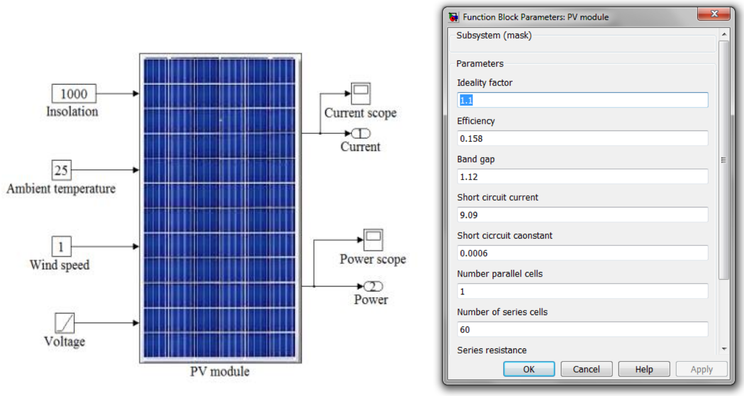

Figure 3. Masked PV module and (b) dialog box of the developed MatLab/simulink model

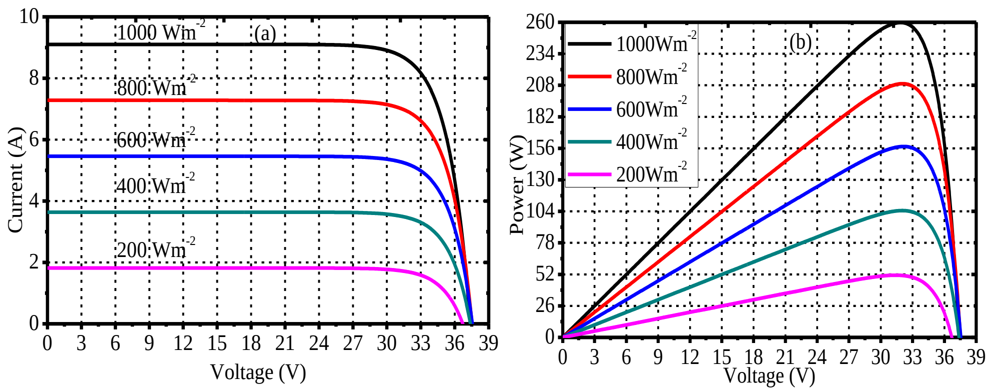

Figure 4. (a) I-V and (b) P-V output characteristics of KT260-6GC-A at various solar irradiance intensities

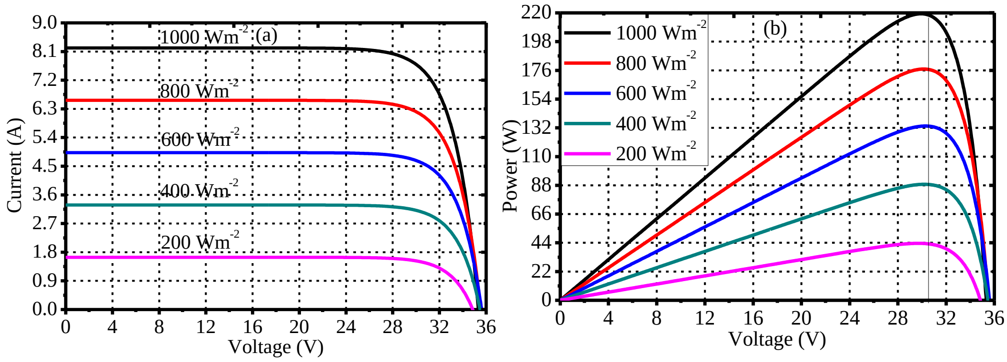

Figure 5. I-V and P-V output characteristics of ND-220(ELF) at various solar irradiance intensities

Interestingly, the simulated I-V and P-V output characteristics were comparable to those provided in the datasheets within acceptable error, confirming the accuracy of the proposed model. For instance, the simulated output powers for the two modules under the standard testing conditions were 260.31 W at 31.98 V and 219.52 W at 29.64 V for KT260-6GC-A and ND-220(ELF) PV modules, respectively. Comparing the latter values with those provided in the datasheets (**Table 1**), the relative errors are estimated at +0.12% and -0.22% for KT260-6GC-A and ND-220(ELF) PV modules, respectively. It is also interesting to note the effects of solar irradiance intensity on the performances of PV modules as presented on Figure 5Figure 6. The I-V and P-V characteristics were simulated at standard conditions of the temperature and wind speed (i.e., $T_{STC} = 25°C$ and $v_{STC} = 1ms^{-1}$). Obviously, the output characteristics are related to solar irradiance intensity. Higher output powers were recorded at higher irradiance intensity.

4. Simulation results and discussion

4.1. Effects of ambient temperature variation on output characteristics of a PV module

Effects of ambient temperature variation on output characteristics of a PV module were analysed using the developed model and the mode KT260-6GC-A was taken as example. The model was simulated by keeping the solar irradiance intensity and the wind at their standard testing conditions values and varying the temperature with a step of 25 0C. Figure 6 shows the I-V and P-V characteristics of a PV module simulated at various ambient temperatures.

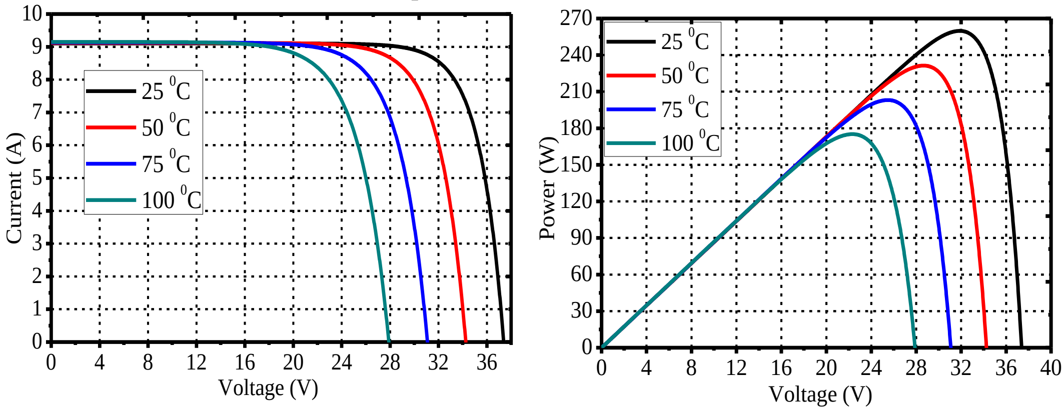

Figure 6. (a) I-V and (b) P-V output characteristics of a PV module at various temperatures

It can be seen that the maximum point voltage and power decreased with an increase of ambient temperature. The increase in ambient temperature leads to a substantive increase in the cell temperature and thus to a reduction in both I-V and P-V outputs of the module. For instance, an increase of 25 ^{0}C from the standard testing conditions led to a reduction in the maximum power output from 260.31 W at 31.98 V to 231.76 W at 28.86 V. It is clear from these results that a cooling system could be needed to keep the PV module at its optimum point.

4.2. Effects of wind speed variation on output characteristics of PV modules

Using the developed matlab/simulink model, effects of wind speed variation on the output characteristics of PV modules were analysed using the model KT260-6GC-A PV. The solar irradiance intensity and the temperature were kept at the standard testing conditions and the output characteristics were simulated at various wind speeds.

Figure 7 shows the I-V and P-V output characteristics of the KT260-6GC-A PV module under various wind speeds. Clearly, higher maximum power point was obtained at higher wind speed. In addition, an increase in wind speed leads to an increase in the heat exchange coefficient for the total surface of the cell (equation 8) and thus to a reduction in the cell temperature. It is evident from the previous analysis that the change in the cell temperature affects the performances of the PV module. The lower the cell temperature, the higher the electrical performance. As can be seen from Figure 7, the highest output power of 274.06 W at 33.54 V was obtained at 15 ms^{-1}. Compared to the standard testing conditions, the enhancement in the output power could be estimated at 5.13%. Since it takes into account effects of wind speed on the performances of PV modules, the developed model could be useful in the design of optimum cooling systems for PV/T systems.

To analyse the output characteristics of a PV module under varying atmospheric conditions, the wind was assumed to follow a Gaussian distribution defined as

$$v(t) = v_{\max} \exp\left(-\frac{(t - t_c)^2}{2\sigma^2} \right) \tag{10}$$

where v_{max} is the maximum wind speed at a given time of the day, t_c is the centre time and σ is the standard deviation of Gaussian function.

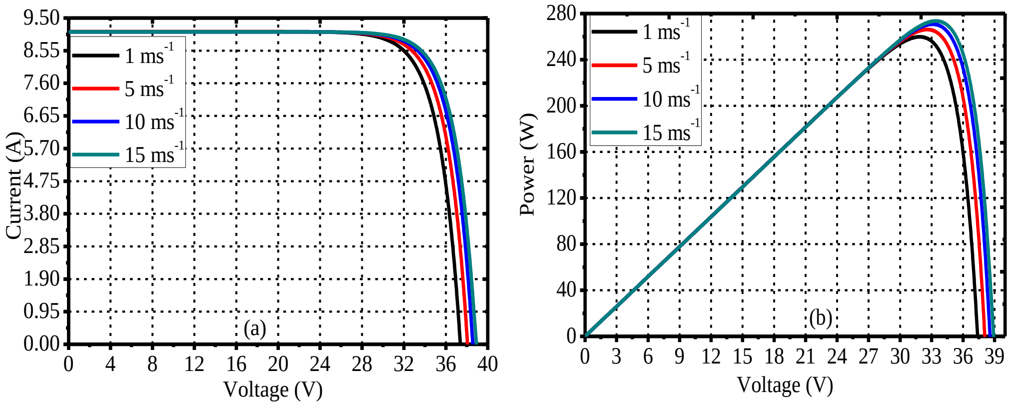

Figure 7. (a) I-V and (b) P-V output characteristics of a PV module at various wind speeds

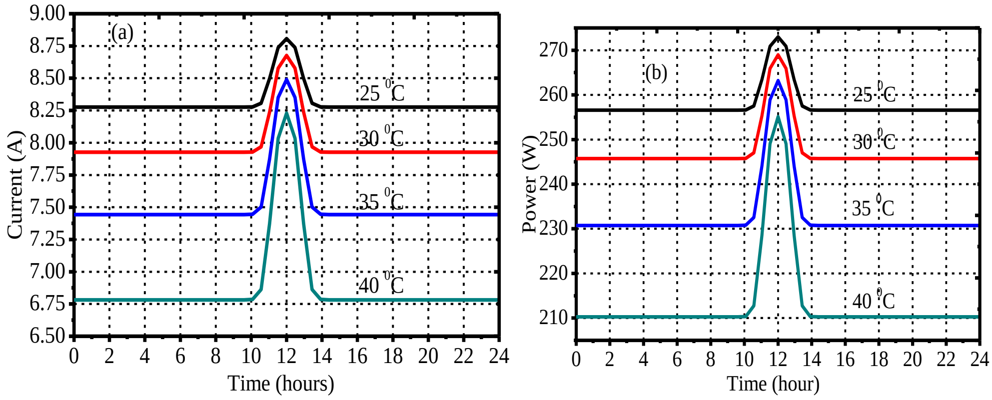

Figure 8. (a) I-V and (b) P-V output characteristics of a PV module during a sample day at various temperatures

The output characteristics of the PV module taken as example were simulated for a sample day with maximum wind speed $v_{max} = 15 ms^{-1}$, centre time $t_c = 12$ and $\sigma = 0.5$. The output characteristics of a PV module for the sample day were simulated at various temperatures ranging from 25 ^{0}C to 40^{0}C for a constant solar irradiance intensity of 1000 Wm^{-2} at the maximum operational voltage (31 V). Figure 8 shows the output current and power as function of voltage at various temperatures. As can be seen from the figure, both the current and the output power are significantly affected by the wind and temperature variations. The optimum output current and output power are 8.81 A and 273.03 W, respectively. It is also interesting to note that, despite the cooling effects of the wind, a slight increase in temperature is followed by a significant reduction in the output characteristics and significant reduction was observed at relatively higher temperature.

5. Conclusion

In this work, a MatLab/Simulink model of a PV module was developed and analyzed under varying environmental conditions. The cell temperature was modeled taking into account the solar irradiance intensity, the ambient temperature and the wind speed as environmental parameters. The accuracy of the developed model was confirmed *via* a comparison of the simulated results and the data provided by the PV module manufacturers. The relative error for the modules taken as examples were estimated at + 0.12% and -0.22% for for KT260-6GC-A and ND-220(ELF) PV modules, respectively. The obtained results confirm that environmental condition variations have a significant influence on the performances of PV modules and should be taken into consideration during the systems design. In addition, the developed model could be a useful tool in designing optimum cooling systems for PV/T systems.

Acknowledgement
This work was financed by the World Bank through the East Africa Higher Education Centers of Excellence (Project ID: P151847), Center of Excellence in Energy for Sustainable Development (ACE-ESD).

6. References

[1] Armstrong S and Hurley W G 2010 A thermal model for photovoltaic panels under varying atmospheric conditions *Appl. Therm. Eng.* **30** 1488–95
[2] Bellia H, Youcef R and Fatima M 2014 A detailed modeling of photovoltaic module using MATLAB *NRIAG J. Astron. Geophys.* **3** 53–61
[3] Chander S, Purohit A, Sharma A, Arvind, Nehra S P and Dhaka M S 2015 A study on photovoltaic parameters of mono-crystalline silicon solar cell with cell temperature *Energy Reports* **1** 104–9
[4] Tsai H L 2010 Insolation-oriented model of photovoltaic module using Matlab/Simulink *Sol. Energy* **84** 1318–26
[5] Nguyen X H and Nguyen M P 2015 Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink *Environ. Syst. Res.* **4** 24
[6] Olukan T A and Emziane M 2014 A comparative analysis of PV module temperature models *Energy Procedia* **62** 694–703
[7] Paul P S 2014 Modeling Comb bined Effect of Tempe erature and Irradiance on o Solar Cell Parame ters by MA ATLAB / Simulink *8th Int. Conf. Electr. Comput. Eng.* 512–5
[8] Villalva M, Gazoli J and Filho E 2009 Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays *IEEE Trans. Power Electron.* **24** 1198–208
[9] Bechouat M, Younsi A, Sedraoui M, Soufi Y, Yousfi L, Tabet I and Touafek K 2017 Parameters identification of a photovoltaic module in a thermal system using meta-heuristic optimization methods *Int. J. Energy Environ. Eng.* **8** 331–41
[10] Abdulkadir M, Samosir A S and Yatim A H M 2012 Modelling and simulation of maximum power point tracking of photovoltaic system in Simulink model *PECon 2012 - 2012 IEEE Int. Conf. Power Energy* 325–30
[11] Krismadinata, Rahim N A, Ping H W and Selvaraj J 2013 Photovoltaic Module Modeling using Simulink/Matlab *Procedia Environ. Sci.* **17** 537–46
[12] Ishaque K, Salam Z and Syafaruddin 2011 A comprehensive MATLAB Simulink PV system simulator with partial shading capability based on two-diode model *Sol. Energy* **85** 2217–27
[13] Vimalarani C and Kamaraj N 2015 Modeling and performance analysis of the solar photovoltaic cell model using Embedded MATLAB *Simulation* **91** 217–32
[14] Khanna V, Das B K, Bisht D, Vandana and Singh P K 2015 A three diode model for industrial solar cells and estimation of solar cell parameters using PSO algorithm *Renew. Energy* **78** 105–13
[15] Díaz-Bernabé J L and Morales-Acevedo A 2015 Photovoltaic module simulator implemented in SPICE and Simulink *2015 12th Int. Conf. Electr. Eng. Comput. Sci. Autom. Control. CCE 2015*
[16] Liu X 2015 Development of Fast Simulation Models for Photovoltaic Generation System Based on Simulink 3265–70
[17] Ayaz R, Nakir I and Tanrioven M 2014 An improved matlab-simulink model of pv module considering ambient conditions *Int. J. Photoenergy* **2014**
[18] Zainal N A, Ajisman and Yusoff A R 2016 Modelling of Photovoltaic Module Using Matlab Simulink *IOP Conf. Ser. Mater. Sci. Eng.* **114**
[19] Schwingshackl C, Petitta M, Wagner J E, Belluardo G, Moser D, Castelli M, Zebisch M and Tetzlaff A 2013 Wind effect on PV module temperature: Analysis of different techniques for an accurate estimation *Energy Procedia* **40** 77–86
[20] Mattei M, Notton G, Cristofari C, Muselli M and Poggi P 2006 Calculation of the polycrystalline PV module temperature using a simple method of energy balance *Renew. Energy* **31** 553–67