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Effect of Solar Irradiance and Temperature on Photovoltaic Module Electrical Characteristics

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Abstract

The electrical characteristics of photovoltaic (PV) module are dependent on solar irradiance and temperature. It consists of short circuit current, open circuit voltage, maximum power, fill factor and efficiency. This paper presents the effect of solar irradiance and temperature on PV module electrical characteristics. A mathematical modeling was developed to characterize the electrical characteristics of PV module using PSpice. A 60 W, 21 V, BP SX 60 multi-crystalline silicon PV module was used in this paper. Under constant solar irradiance and difference temperature or inversely were tested to the PV module, its electrical characteristics shown. The result shows that if the solar irradiance is constant and the temperature increase will cause the open circuit voltage, the maximum power and the efficiency decrease, if the temperature constant and solar irradiance increase will cause the short circuit current, the open circuit voltage, the maximum power and the efficiency increase.

Keywords— Solar irradiance; Temperature; PV module; electrical characteristics

1. Introduction

The major factors which influence the electrical design of the PV module are solar irradiance, tilt angle of PV module, load matching for maximum power and operating temperature [1]. The electrical characteristics of the PV module are generally represented by the current versus voltage (i-v) curve. They are influenced by temperature and solar irradiance, and they influence on the design of PV module system [2].

Temperature is an important consideration in the operation of PV module system [3]. At lower temperatures, PV module systems produce more power. For higher temperature, optimum operation requires modification of electrical load and removal of excess heat. At high temperatures, two predominating effects can cause efficiency to drop. As thermal energy increases, lattice vibrations interface with the free passing of charge carries and the junction begins to loss its power to separate charges.

The efficiency losses for PV systems can be minimized in the presence of temperature variations. In most cases, good solutions are a temperature-dependent charge controller or a maximum power tracker. Both devices improve the overall system efficiency at higher temperature where the performance is poor [3].

A c-Si module has been test to get its electrical characteristic by [4], 1000 W/m^2 of solar irradiance and temperature from 15 ^{0}C to 65 ^{0}C were fallen to the surface of the PV module. Its electrical characteristic was observed, the result shown that for solar irradiance was constant and temperature increased, its short circuit current would be constant, open circuit voltage and maximum power would decrease. Effect of temperature on electrical characteristic of a photovoltaic module has been tested by [2], shown that for 975.4 W/m^2 and temperature were 25.1 ^{0}C, 45.9 ^{0}C and 55.6 ^{0}C resulted the maximum power were 44.98 W, 40.06 W and 38.11 W, respectively. The open circuit voltage varies linearly with temperature if the temperature were increased [5].

The temperature of 25 ^{0}C, the solar irradiance of 600 W/m^2, 800 W/m^2 and 1000 W/m^2 (increased solar irradiance) were tested to a c-Si PV module by [4], the result shown that the short circuit current, open circuit voltage, and maximum power would increase. The effect of solar irradiance on a photovoltaic module performance was tested by [2]

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also, shown that for the constant temperature of 37.7 ^{0}C, the solar irradiance of 626 W/m^2 , 831 W/m^2 and 974 W/m^2 resulted the maximum power were 28.27 W, 36.55 W and 41.85 W, respectively. Research by [5] shown that the short circuit current increases almost linier, the fill factor is not significantly influenced by the solar irradiance, the maximum power point varies sub linearly with solar irradiance.

A behavioural model has been developed by [6] to characterize current, voltage and power of the photovoltaic modules as function of temperature and solar irradiance. Calculated diagrams are compared with diagrams of two photovoltaic module data sheet.

This paper presents a mathematical modeling to observe a PV module characteristic. A poly-crystal silicon PV module was tested with constant solar irradiance and varied temperature, also with constant temperature and varied solar irradiance, both the PV module performance observed using PSpice software. The observed PV module characteristics are the short circuit current, the open circuit voltage, the maximum power, the fill factor and the efficiency.

2. Data and Methodology

2.1. PV Data

A 60 W, 21 V, BP SX 60 multi-crystalline silicon PV module was used in this paper. This PV module consists of 36 solar cells configured in series strings. The complete data of the PV module is shown in Table 1.

Table 1. Electrical parameter of poly-crystal silicon PV module

	BP SX 60
Maximum power (P_{max})[2]	60W
Voltage at P_{max} (V_{mp})	16.8V
Current at P_{max} (I_{mp})	3.56A
Guaranteed minimum P_{max}	55W
Short-circuit current (I_{sc})	3.87A
Open-circuit voltage (V_{oc})	21.0V
Temperature coefficient of I_{sc}	(0.065±0.015)%/°C
Temperature coefficient of V_{oc}	-(80±10)mV/°C
Temperature coefficient of power	-(0.5±0.05)%/°C
NOCT	47±2°C
Maximum series fuse rating	20A

2.2 Mathematical Modelling of PV Module Characteristic

The most popular photovoltaic module is a particular case of a series string of solar cells. In terrestrial application the PV standard modules are composed of a number solar cells connected series. The number is usually 33 to 36 but different associations are also available. The PV module characteristic is the result of the voltage scaling of the $I(V)$ characteristic of a single solar cell. Consider the $I(V)$ characteristic of a single solar [7], [8]:

$$I = I_L - I_0\left(e^{\frac{V+IR_s}{nV_T}} - 1\right) - I_{02}\left(e^{\frac{V+IR_s}{2V_T}} - 1\right) - \frac{V+IR_s}{R_{sh}} \quad (1)$$

Consider some simplifying assumptions, in particular that the shunt resistance, R_{sh}, of a solar cell is large and its effects can be neglected, and that the effects of the second diode are also negligible. So, assuming $I_{02} = 0$ and $R_{sh} = \infty$, equation (1) becomes

$$I = I_{sc} - I_0\left(e^{\frac{V+IR_s}{nV_T}} - 1\right) \quad (2)$$

where $I_{sc} = I_L$ has also been assumed.

The scaling rules of voltage, currents and resistances when a matrix of $N_s x N_p$ solar cells is considered are the following:

$$I_M = N_P I \quad (3)$$

$$I_{scM} = N_p I_{sc} \quad (4)$$

$$V_M = N_s V \quad (5)$$

$$V_{ocM} = N_s V_{oc} \quad (6)$$

where subscript M stands for ‘Module’ and subscript without M stand for a single solar cell. The scaling rule of the series resistance is the same as that of an $N_s x N_p$ association of resistors:

$$R_{sM} = \frac{N_s}{N_p} R_s \quad (7)$$

Substituting in equation (2),

$$\frac{I_M}{N_p} = \frac{I_{scM}}{N_p} - I_{01}(e^{\frac{\frac{V_M}{N_s} + \frac{I_M N_p}{N_p N_s} R_{sM}}{nV_T}} - 1) \quad (8)$$

$$I_M = I_{scM} - N_p I_{01}(e^{\frac{V_M + I_M R_{sM}}{nN_s V_T}} - 1) \quad (9)$$

Moreover, from equation (2) in open circuit, I_0 can be written as:

$$I_0 = \frac{I_{sc}}{(e^{\frac{V_{oc}}{nV_T}} - 1)} \quad (10)$$

Using now equation (4) and (6)

$$I_0 = \frac{I_{scM}}{N_p(e^{\frac{V_{ocM}}{nV_T N_s}} - 1)} \quad (11)$$

2.3 Temperature Effect

Consider the electrical characteristic in the p-n step junction. In the ideal diode (with low level injection), the diffusion current is [3]:

$$J = J_s\left(e^{\frac{qV}{kT}} - 1\right) = \left(\frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{p0}}{L_n}\right)\left(e^{\frac{qV}{kT}} - 1\right) \quad (12)$$

where J_s is the saturation current density, D is the diffusion coefficient and L is the diffusion length of electrons or holes, which is equal to $\sqrt{D\tau}$ where τ is the minority lifetime. The p_{n0} and n_{p0} represent electron and hole densities in n-type region and p-type region at thermal equilibrium. Also, n_i is the intrinsic carrier density which has the relationship of $p_{n0} n_{p0} = n_i$.

The short-circuit circuit tends to increase with increasing temperature. When temperature increase, the diffusion coefficient diffusion D, the minority life time τ, the diffusion length L and the intrinsic carrier density will increase. The change of these parameters will enhance diffusion, i.e, a larger D. The photocurrent generated by the solar cell is the sum of electron diffusion current, hole diffusion current and dominant generation current in the depletion region. The generation current in the ideal depletion region is independent of temperature, so the increase of diffusion will result in an increase of photocurrent.

The open circuit voltage tends to decrease with increasing temperature. The open circuit voltage V_{oc} can be obtained from the solar cell characteristic equation (1).

$$V_{oc} \cong \frac{kT}{q} \ln\left(\frac{I_{ph}}{I_s} + 1\right) \cong \frac{kT}{q} \ln\left(\frac{I_{ph}}{I_s}\right) \quad (13)$$

When temperature increases, the amount of saturation current will increase more than the amount of photocurrent and therefore makes V_{oc} decreased rapidly.

2.4 Solar Irradiance Effect

Applying the open circuit condition, $I = 0$, to the $I(V)$ equation is given by [6]:

$$I = 0 = I_{sc} - I_0\left(e^{\frac{V_{oc}}{V_T}} - 1\right) \quad (14)$$

The open circuit voltage is given by :

$$V_{oc} = V_T \ln\left(1 + \frac{I_{sc}}{I_0}\right) \quad (15)$$

From equation (15), it can be seen than the value of the open circuit voltage depends, logarithmically on the I_{sc}/I_o ratio. This means that under constant temperature the value of the open circuit voltage scales logarithmically with the short circuit which, in turn scales linearly with irradiance resulting in a logarithmic dependence of the open circuit voltage with irradiance. This is also an important result indicating that the effect of the irradiance is much larger in the short circuit current than in the open circuit value.

2.5 Photovoltaic Module Characteristics

In this paper the photovoltaic module characteristics are:

1. Short circuit current (I_{SC})

The short circuit current (I_{SC}) represent to the maximum current ($I_{\max}$) that passes through the cell that corresponds to the short circuit condition when the impedance is low. It occurs at the beginning of the sweep when the voltage is zero. In an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation.

$$I_{SC} = I_{\max} \text{ , at } V = 0 \quad (16)$$

2. Open circuit voltage (V_{OC})

The open circuit voltage (V_{OC}) is the maximum voltage difference across the cell, and it occurs when there is no current passing through the cell.

$$V_{OC} = V_{\max} \text{ , at } I = 0 \quad (17)$$

3. Maximum power ($P_{\max}$)

The power produced by the cell in watts can be easily calculated along the I-V characteristic curve in Figure 5. At the I_{SC} and V_{OC} points, the power will be zero and the maximum value for power will occur between the two points. The voltage and current at this maximum power point are denoted as $V_{\max}$ and $I_{\max}$ respectively.

$$P_{\max} = V_{\max} x I_{\max} \quad (18)$$

4. Fill factor (FF)

The Fill Factor (FF) is essentially a measurement of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (P_T) that would be output at both the open circuit voltage and short circuit current together. FF can also be interpreted graphically as the ratio of the rectangular areas, its larger desirable, and corresponds to an I-V characteristic curve in Figure 5. Typical fill factor range from 0.5 to 0.82.

$$FF = \frac{P_{\max}}{P_T} = \frac{V_{\max} x I_{\max}}{V_{OC} x I_{SC}} \quad (19)$$

5. Efficiency (η)

Efficiency is the ratio of the electrical power output (P_{out}), compared to the solar power input (P_{in}) into the PV cell. P_{out} can be taken to be $P_{\max}$ since the solar cell can be operated up to its maximum power output to get the maximum efficiency.

$$\eta = \frac{P_{out}}{P_{in}} \qquad \eta_{\max} = \frac{P_{\max}}{P_{in}} \quad (20)$$

P_{in} is taken as the product of the irradiance of the incident light, measured in W/m^2 or in suns (1000 W/m^2), with the surface area of the solar cell (m^2).

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3. Results and Discussion

3.1. Validation of The Mathematical Modelling Using PSpice

To validate the mathematical modeling of PV module characteristics using PSpice, the data of PV module as shown in Table 1 was simulated for condition of solar irradiance and temperature were 1000 W/m^2 and 25 ^{0}C, respectively. The current-voltage and power-voltage curve are shown in Figure 1 and 2.

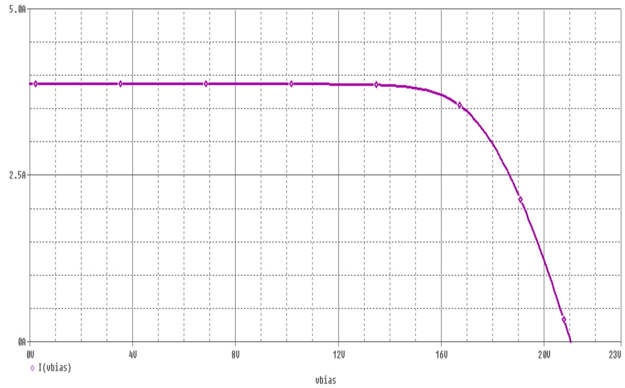

Figure 1. Current-voltage curve of PV module

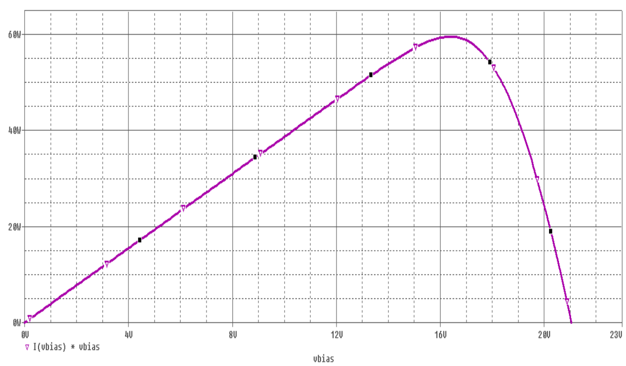

Figure 2. Power-voltage curve of PV module

The PV module characteristics for solar irradiance of 1000 W/m^2 of and temperature of 25 ^{0}C are shown in Table 2.

Table 2. The PV module characteristics for 1000 W/m^2 of solar irradiance and 25 ^{0}C of temperature

Electric Characteristics	Data Sheet	Simulation
Short circuit current (A)	3.87	3.87
Open circuit voltage (V)	21	21.04
Maximum power (W)	60	59.55

The PV module characteristics can be validated using statistical analysis, exactly using percentage error (e) [9]. A relative percentage error between -10% and +10% is considered acceptable.

Based on electric characteristics as shown in Table 1, the percentage error of the short circuit current, the open circuit voltage and the maximum power are 0 %, -0.19% and 0.75 %. These percentage errors indicate that the mathematical modeling of PV module characteristic is considered acceptable. The negative percentage error indicates tendency over-simulate to the data sheet of PV module. The model described in this simulation is based on Standard Test Condition (STC) defined with nominal solar irradiance level 1000 W/m^2 and nominal temperature 25 ^{0}C of Air Mass (AM) 1.5 G solar spectral contents. This STC according to the electrical characteristics of a PV module from the value of the main PV magnitudes available for a commercial module: short circuit current, open circuit voltage, maximum power and the number of cells connected.

3.2. Solar Irradiance effect

The solar irradiance effect on electrical characteristics of PV module are simulated under solar irradiance of 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2, 1000 W/m^2 and constant temperature of 25 ^{0}C. The current-voltage and power-voltage curve of PV module are shown in Figure 3 and 4, respectively. The Figure 3 shows that under constant temperature the value of the open circuit voltage scales logarithmically with the short circuit current which, in turn scales linearly with the solar irradiance resulting in a logarithmic dependence of the open circuit voltage with the solar irradiance. The solar irradiance effect on the electrical characteristics of PV module is much larger in the short circuit current than in the open circuit voltage. The value of the short circuit current and the open circuit voltage of each the solar irradiance can be seen in Table 3.

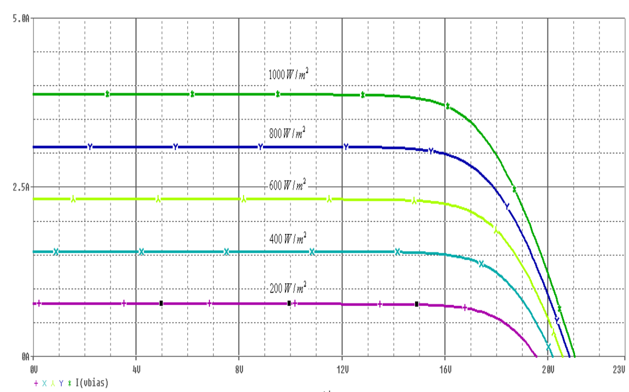

Figure 3. Current-voltage curve of PV module with 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2, 1000 W/m^2 of solar irradiance and 25 ^{0}C of constant temperature

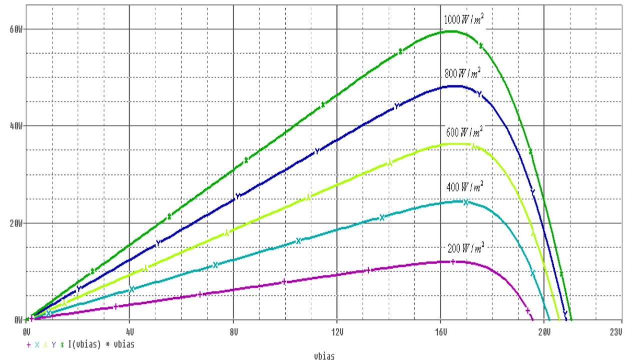

Figure 4. Power-voltage curve of PV module with 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2, 1000 W/m^2 of solar irradiance and 25 ^{0}C of constant temperature

Figure 4 shows that under constant temperature, if the solar irradiance increase cause the maximum power of PV module will increase. The value of the PV module maximum power of each the solar irradiance can be seen in Table 3.

Table 3 shows that under constant temperature, if the solar irradiance increase cause the electrical characteristics of PV module (short circuit current, open circuit voltage, maximum power, and efficiency) will increase, the fill factor is fulfilled what discussed by [8].

Table 3. The PV module characteristics with 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2, 1000 W/m^2 of solar irradiance and 25 ^{0}C of constant temperature

Electrical Characteristics	**Solar irradiance (W/m^2)**				
	200	**400**	**600**	**800**	**1000**
I_{sc} (A)	0.77	1.55	2.32	3.10	3.87
V_{oc} (V)	19.53	20.19	20.55	20.84	21.04
$P_{\max}$ (W)	12.02	24.38	36.49	48.23	59.55
FF	0.8	0.78	0.77	0.75	0.73
η (%)	20	40.63	60.82	80.38	99.25

3.3. Temperature effect

The temperature effect on the electrical characteristics of PV module are simulated under constant solar irradiance of 1000 W/m^2 and temperature of 25 ^{0}C, 35 ^{0}C, 45 ^{0}C, 55 ^{0}C, 65 ^{0}C. The current-voltage and power-voltage curve of PV module are shown in Figure 5 and 6, respectively.

Figure 5 shows that under constant solar irradiance and difference temperature, the open circuit voltage and short circuit current of PV module will be influenced significantly and slightly, respectively. The open circuit voltage tends to decrease with increasing temperature. When temperature increase, the amount of saturation current will increase more than the amount of photocurrent and therefore makes the open circuit voltage decreased rapidly [3]. The short-circuit circuit tends to increase with increasing temperature. When temperature increase, the diffusion coefficient diffusion D, the minority life time τ, the diffusion length L and the intrinsic carrier density will increase. The change of these parameters will enhance diffusion, i.e, a larger D. The photocurrent generated by the PV module is the sum of electron diffusion current, hole diffusion current and dominant generation current in the depletion region. The generation current in the ideal depletion region is independent of temperature, so the increase of diffusion will result in an increase of photocurrent [3]. The value of the short circuit current and the open circuit voltage of each the temperature can be seen in Table 4.

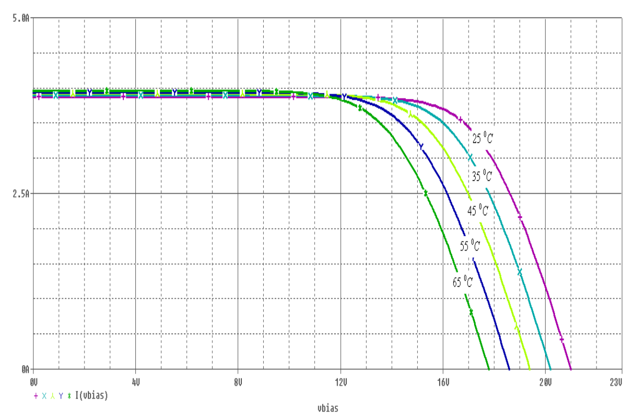

Figure 5. Current-voltage curve of PV module under 1000 W/m^2 of constant solar irradiance and difference temperature

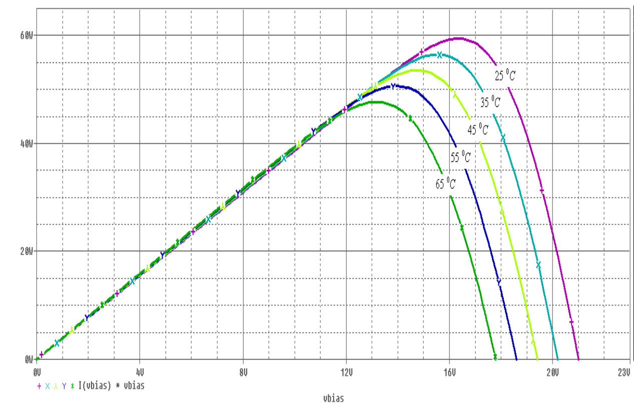

Figure 6. Power-voltage curve of PV module under 1000 W/m^2 of constant solar irradiance and difference temperature

Figure 6 shows that under constant solar irradiance, if the temperature increase cause the maximum power of PV module will decrease. The value of the PV module maximum power of each the temperature can be seen in Table 3.

Table 4 shows that under constant solar irradiance, if the temperature increase cause the open circuit voltage, maximum power, and efficiency of PV module will decrease, but the short circuit current will increase, the fill factor is fulfilled what discussed by [8].

Table 4. The PV module characteristics under temperature of 25 ^{0}C, 35 ^{0}C, 45 ^{0}C, 55 ^{0}C, 65 ^{0}C and constant solar irradiance of 1000 W/m^2

Electrical Characteristics	**Temperature (^{0}C)**				
	25	**35**	**45**	**55**	**65**
I_{sc} (A)	3.87	3.89	3.92	3.94	3.96
V_{oc} (V)	21.04	20.23	19.39	18.60	17.80
$P_{\max}$ (W)	59.55	56.48	53.55	50.61	47.68
FF	0.73	0.72	0.70	0.69	0.68
η (%)	99.25	94.13	89.25	84.35	79.47

Conclusion

The electrical characteristics of PV module are dependent on solar irradiance and temperature. If the solar irradiance is constant and although the temperature increase will cause the short circuit current still constant, if the solar irradiance is constant and the temperature increase will cause the open circuit voltage, maximum power and efficiency decrease, if the temperature constant and solar irradiance increase will cause the short circuit current, open circuit voltage, maximum power and efficiency increase.

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