IMPACT OF SOLAR RADIATION AND TEMPERATURE LEVELS ON THE VARIATION OF THE SERIES AND SHUNT RESISTORS IN PHOTOVOLTAIC MODULES

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Abstract

It is well-known that the efficiency of silicon-based photovoltaic modules decreases with temperature. This paper discusses the variation of series and shunt resistances of PV modules with temperature which affect their efficiencies. A tool, "MY PV TOOL", has been developed to help in simulating the variations of series and shunt resistances for different levels of solar radiation and temperature using experimental measurements as well as theoretical equations of the PV module.

Keywords: *Solar Radiation, Solar Temperature, Shunt Resistors, Photovoltaic Modules*

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1. INTRODUCTION

The use of fossil fuel-based and nuclear energy constitutes today the bulk of total energy needed worldwide. The photovoltaic (PV) systems with other renewable energy forms are potential ways to alleviate the problem of energy resources that we may face in the coming years. A PV cell absorbs sunlight and converts it into electricity [1, 2, 3]. A part of the absorbed sunlight energy is converted into electricity while the other part is converted to heat. [4]. This generated heat in addition to the possible increase in the ambient temperature affects the material properties of a PV cell which leads to negatively alter the power output of the PV cell, and consequently its efficiency [5, 6,7]. To minimize the problem of raising temperature in PV modules, a cooling method of the module's surface is proposed to extract the heat and hence alleviate the heat problem. The heating rate based on the operating conditions (solar radiation, ambient temperature, and ambient temperature at sunrise) will determine when to start cooling the PV modules. The proposed cooling method is meant to maintain a specific PV temperature that corresponds to the maximum output power as per the datasheet of the PV module [8, 9].

Several studies have been conducted on the so-called PV/T systems. The PV/T is a PV system that circulates a liquid [10, 11] or air [12, 13, 14, 15, 16] flow at a lower temperature compared to the PV module in order to extract any developed heat and consequently ensure a cooler operating environment for the module.

Akbarzadeh and Wadowski [17] proposed a hybrid PV/T solar system, and concluded that water helps the PV module in increasing its output power by almost 50% using water flow in addition to keeping the PV surface at below 46°C when exposed to solar radiation for a period of 4 h.

Chaniotakis [18] suggested another hybrid PV/T solar system where both water and air flow were applied and investigated. The water-based cooling system was proved to be more efficient than the air based cooling system [11].

Tonui and Tripanagnostopoulos [16] proposed a PV/T Air system to study the cooling effect on the PV module with either forced or natural convection. Under natural convection, the PV module temperature could reach up to 12°C in the early afternoon during sunny days. For the forced convection, the experiments were conducted with three different cases, i.e., Case A – PV/T Air with fins, Case B – PV/T Air with thin metallic sheet, and Case C – PV/T Air normal. The study showed a significant efficiency of 30 % (case A), 28 % (case B), and 25 % (case C).

In the current research work, the main objective is to compare the electrical output power of a PV module with and without cooling. Then a theoretical model of the PV module is developed in order to study the correlation between thermal (i.e. heat) and electrical (i.e. series and shunt resistances) effects on the behavior of the PV module.

2. EXPERIMENTAL SETUP

An experimental setup was designed to investigate the thermal and electrical performances of the PV/T air system. The electrical characteristics of the PV module used in this experiment are shown in Table 1.

Table1: The electrical characteristics of the PV module

Maximum Power	4.6 W
Optimum Operating Voltage	18.3 V
Optimum Operating Current	251 mA
Open-Circuit Voltage	20.8 V
Short-Circuit Current	260 mA

The experiment was conducted at different levels of solar irradiance and different load resistances in order to observe the behavior of the PV module in term of electrical output power. The steps of the experiment are summarized below.

2.1. Reference PV module:

The PV module was placed and tested under the average ambient temperature of 25°C at a specified position perpendicular to the light direction. Using a pyranometer, the halogen lamp simulating the sun was placed at a certain distance away from the PV panel in order to obtain the required solar irradiances (650,860, and 960 W/m^2).

All measuring devices were connected to the PV system, including voltmeters, ammeters and thermocouples. The halogen lamp was turned on, and the experiment was conducted at different irradiances and resistances for an appropriate time. The output voltages and currents were recorded in addition to the temperatures of the PV module during the experiment.

2.2. Thermal Photovoltaic System (PV-T)

The return air from air conditioning systems is used to reduce the surface temperature of PV modules. A part (the exhaust air) of the return air will be used to cool down the surface temperature of the PV module while the other part will be re-used in the HVAC system. Therefore, the return air from HVAC system reduces the temperature of the PV module's surface. As mentioned above, currents, voltages, and temperatures have been recorded for the Reference PV system. Several measurements were repeated here in order to monitor the behavior of the PV module while the return air of HVAC is in action.

The back of the PV module is considered insulated and the heat transfer is occurring only through its upper surface. The heat transfer from the solid surface to the adjacent fluid layer is done via a pure convection described by the following equation [19] (all symbols are listed in Table 3):

$$G = Q_{conv} = h \times (T_{surf} - T_{fluid}) \tag{1}$$

Therefore, the surface temperature can be expressed as follows [19]:

$$T_{surf} = \frac{G}{h} + T_{fluid} \tag{2}$$

The convection heat transfer coefficient, in general, varies along the flow direction. The mean or average heat transfer coefficient for a surface is determined by averaging the local heat transfer coefficient over the entire surface.

In order to calculate the heat transfer coefficient, the type of flow should be determined by calculating the Reynolds number [19]:

$$Re = \frac{V_{el} \times L}{v} \tag{3}$$

The average Nusselt number over the flat plate is [19]:

For laminar flow: $Nu = \frac{hL}{K_{cond}} = 0.453\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33}$

$$\text{with } \begin{cases} \mathrm{Re} < 5 \times 10^5 \\ \mathrm{Pr} > 0.6 \end{cases} \tag{4}$$

For mixed flow: $Nu = \frac{hL}{K_{cond}} = (0.037\,\mathrm{Re}^{0.8} - 871)\,\mathrm{Pr}^{0.33}$ with

$$\begin{cases} \mathrm{Re} < 10^8 \\ 0.6 \le \mathrm{Pr} \le 60 \end{cases} \tag{5}$$

3. SIMULATION SETUP

3.1. Solar cell model

The model is based on the basic electrical circuit of a PV solar cell including the influence of solar irradiation and temperature fluctuations. The basic electrical circuit model of a PV cell contains a current source (I_{ph}) connected in parallel with a diode, since it produces current when it is illuminated and acts as a diode in darkness. The equivalent circuit model also includes a shunt and series internal resistances represented by resistors R_s and R_{sh} as shown in Figure 1.

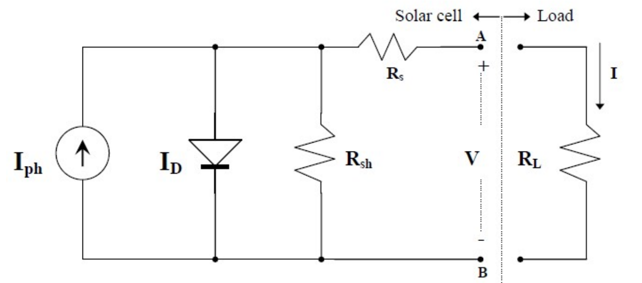


Figure 1: Basic electrical circuit model of a PV cell [20]

The physical structure of an ideal solar cell is a semi-conductor p–n junction that is when subjected to sun radiations the following equations apply:

$$I = I_{ph} - I_{DIODE} \tag{6}$$

$$I_{DIODE} = I_0 \cdot \left[\exp\left(\frac{q \cdot V}{A \cdot k \cdot T_{surf}} \right) - 1 \right] \tag{7}$$

Based on equations (6) and (7), the current–voltage characteristic of a PV module can be described by equations (8) and (9) [21, 22].

$$V = \frac{A \cdot k \cdot T_{surf}}{q} \cdot \ln\left(\frac{I_{ph} + I_0 - 1}{I_0}\right) - I \cdot R_s \tag{8}$$

$$I = I_{ph} - I_0 \cdot \left[\exp\left(\frac{q \cdot (V + I \cdot R_s)}{A \cdot V_T}\right) - 1\right] - \left(\frac{V + I \cdot R_s}{R_{sh}}\right) \tag{9}$$

$$V_T = \frac{N_s \cdot k \cdot T_{surf}}{q} \tag{10}$$

Equations (8) and (9) give the voltage of a single solar cell. In the case of a PV module the full voltage is obtained by multiplying the cell's voltage by the number of cells connected in series. However, the PV cell's current I can be obtained by dividing the module's current by the number of cells connected in parallel before being used in eq. (9), which is only valid for a certain cell operating temperature T_{surf} with its corresponding solar irradiation level G [23].

The change in temperature and solar irradiation usually affect the voltage and current outputs of the PV array. Hence, the effects of the variations in temperature and solar irradiation levels should also be included in the final PV module's model. These effects are taken into consideration using the approach of Burech and al. [23].

$$I_{ph} = \left[I_{phr} + K_i \cdot (T_{surf} - T_{ref})\right] \cdot \frac{G}{Gref} \tag{11}$$

$$I_0 = \left[I_{0r} \cdot \left(\frac{T_{surf}}{T_{ref}}\right)^3\right] \cdot \exp\left[\frac{q \cdot E_g}{k \cdot A} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T_{surf}}\right)\right] \tag{12}$$

Based on Burech's method, for known temperature and solar irradiation values, a model is obtained and can be modified to handle different cases of temperature and irradiation levels. Let (11) be the benchmark model for the known operating temperature (T_{surf}) and known solar irradiation level (G) as given in the specification [24].

I_{ph} exhibits a linear relationship with light intensity. I_0 is also a temperature dependent parameter. Values of I_{ph} and I_0 are given by (11) and (12) [21]

The saturation reverse current I_{0r} at reference temperature T_{ref} is given by the following equation [24]:

$$I_{0r} = \frac{I_{scr,cell}}{\exp\left(\frac{V_{ocr,cell}}{A \cdot V_T}\right)} \tag{13}$$

The open circuit voltage (V_{oc}) and short circuit current (I_{sc}) are important parameters associated with the I-V characteristics of the PV module. These parameters are subject to variations in the atmospheric conditions. Both I_{sc} and V_{oc} can be calculated under different atmospheric conditions using the following equations [21]:

$$I_{sc,cell} = \left[I_{scr,cell} + K_i \cdot (T_{surf} - T_{ref})\right] \cdot \frac{G}{Gref} \tag{14}$$

$$V_{oc,cell} = V_{ocr,cell} + K_v \cdot (T_{surf} - T_{ref}) \tag{15}$$

3.1.1. Effect of R_s and R_{SH}

The maximum voltage and current from a solar cell are respectively I_{sc} and V_{oc}. While the power developed from the PV cell at these maximums is zero. In order to determine the maximum power from a solar cell, we have used the fill factor "FF" which represents the ratio of the maximum power given by the solar cell to the product of V_{oc} and I_{sc}.

$$FF = \frac{V_{Mp} \cdot I_{MP}}{V_{OC} \cdot I_{SC}} \tag{16}$$

The variables FF_S and FF_{SH} have been considered also, which represent the impact of series and shunt resistances on FF respectively.
The effect of series and shunt resistances alone on the fill factor is described respectively by (17) and (18)

$$FF_S = FF_o\left(1 - 1.1 r_S\right) + \frac{r_S^2}{5.4} \tag{17}$$

$$FF_{SH} = FF_o\left(1 - \frac{V_{OC} + 0.7}{V_{OC}} \frac{FF_o}{r_{SH}}\right) \tag{18}$$

Where FF_0 is the fill factor before variations due to shunt and/nor series resistance.
To combine the effect of both series and shunt resistances, the expression for FF_{SH}, derived above, can be used with FF_0 replaced by FF_s [20]. Then the resulting equation becomes;

$$FF_{SH} = FF_s \cdot \left(1 - \frac{V_{OC} + 0.7}{V_{OC}} \cdot \frac{FF_S}{r_{SH}}\right) \tag{19}$$

and by combining the equations (17) and (18), the net equation for FF becomes;

$$FF = FF_0 \cdot \left\{(1 - 1.1 r_S) + \frac{r_S^2}{5.4}\right\} \cdot \left\{1 - \frac{V_{OC} + 0.7}{V_{OC}} \cdot \frac{FF_0}{r_{SH}} \cdot \left[(1 - 1.1 r_S) + \frac{r_s^2}{5.4}\right]\right\} \tag{20}$$

3.1.2. Effect of temperature on the material parameters

Temperature is a paramount factor that alters the band gap of semiconductor devices. Most of the semiconductor parameters are prone to changes with temperature [7]. In fact, temperature and the energy of electrons are deeply correlated. A decrease in the band gap energy of a semiconductor due to an increase in temperature can be viewed as an increase in energy of its electrons. Therefore, rising the temperature of a semiconductor reduces its band gap energy.

Being a semiconductor device, the open circuit voltage V_{OC} of a solar cell is affected by an increase in temperature.

As mentioned above, the series and shunt resistances are mightily affected by V_{OC}. Therefore, any change in temperature affects the values of r_S and r_{SH}.

3.1.3. Modeling using MATLAB®/GUI

Based on the mathematical equations of the different parameters described above, a PV interface "*MY PV TOOL*" has been implemented in MATLAB®/GUI. The purpose of this tool is to determine the theoretical model of a PV module under different constraints (temperature and solar radiation).
The developed tool '*'MY PV TOOL*'' is shown in figure 2. This tool includes three different parts: *PV cell*, *PV MODULE* and *Output*.

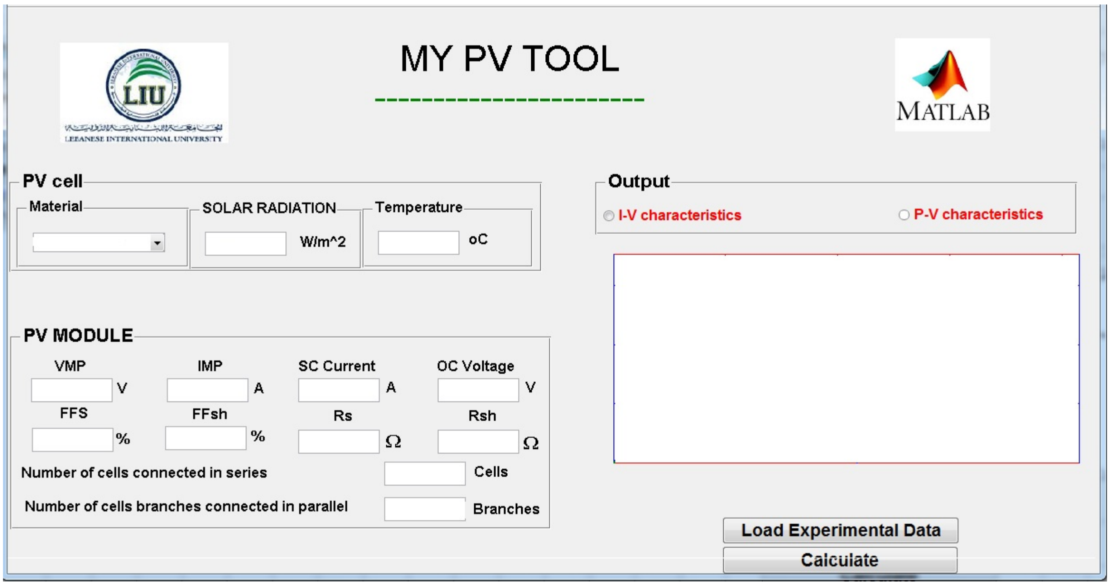


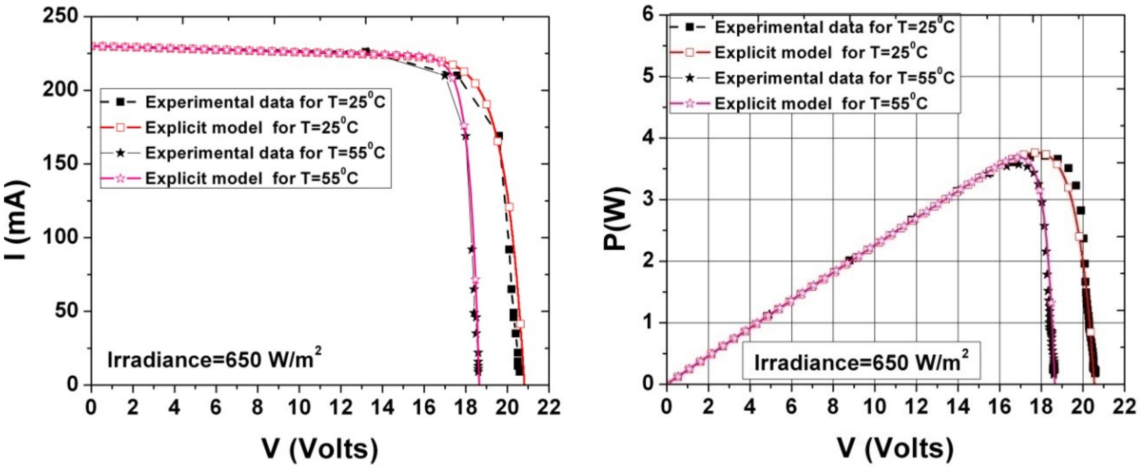
Figure 2: MY PV TOOL

The *''PV cell''* part is composed of the following inputs:
- *Material*: this input describes the type of PV cell under study. Mono and polycrystalline solar cells are considered in this tool.
- *SOLAR RADIATION* and *Temperature*: are the two investigated input constraints in this model.

The ''*PV MODULE*'' part includes the following parameters:
Solar cell parameters (V_{OC}, I_{SC}, V_{MP}, I_{MP}, *number of cells connected in series and parallel*).
Fill factor parameters (FF_S and FF_{SH}).
The ''*Output panel*'' part displays the current vs. voltage or the electric power vs. voltage of the PV module.
As mentioned above, the main idea behind this tool is to determine the theoretical model of a given PV module and analyze the effects of temperature and irradiance on R_S and R_{SH}. Experimental and theoretical data of the PV and solar cell are used in "MY PV TOOL" to determine the real values of R_S and R_{SH}. The two curves describing the experimental and theoretical data are matched by adjusting manually the fill factor parameters (FF_S and FF_{SH}) at 25°C and 960 W/m^2 which lead to determine automatically the real values of R_S and R_{SH} for the other temperature and irradiances.

4. RESULTS AND DISCUSSION

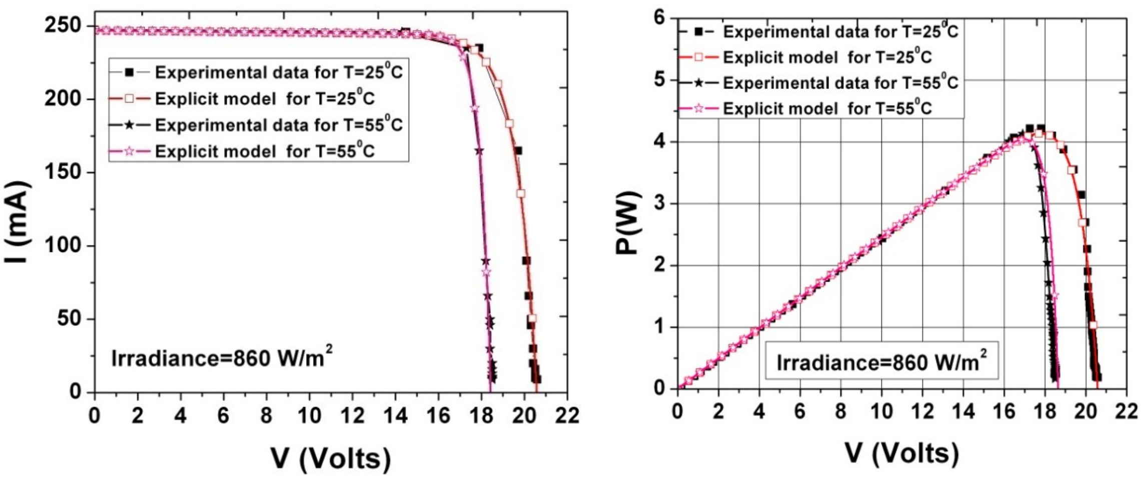
For the PV module having the electrical characteristics shown in Table 1 and using "MY PV TOOL", the I-V as well as P-V curves was obtained for two levels of temperatures T = 25°C and T = 55°C. These two values of temperature are chosen in order to show the effect of Air cooling technique on the efficiency. In fact, without Air, the PV panel reached a temperature of55°C. However, when using Air-cooling system the temperature of the PV panle decreased to the level of the ambient temperature which is 25°C. In addition, I-V and P-V curves at 25°C with and without Air- cooling are very closed together in term of value and shape. The solar radiation level was set to 650 W/m^2.The fill factors FF_s and FF_{sh} were varied until having the experimental and modeling curves as close as possible to each other (i.e. match) as seen in figure 3. The values of R_s and R_{sh} will be recorded which represent respectively the effective series and shunt resistances of the PV module at the specified temperature and irradiance.



(a) (b)

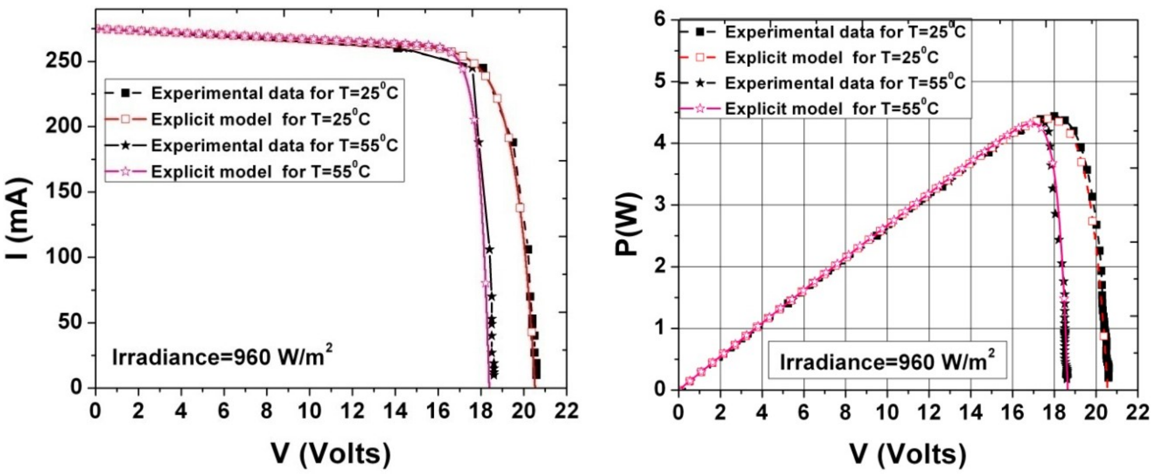
Figure 3: Experimental and modeling curves for an irradiance level of 650 W/m^2 (a)I-V (b) P-V

Using “MY PV TOOL”, the simulations have been repeated for irradiance levels of 860 W/m^2 and 960 W/m^2. The results are shown in figures 4 and 5. A summary of all simulation results is shown in table 2.



(a) (b)

Figure 4: Experimental and modeling curves for an irradiance level of 860 W/m^2 (a) I-V (b) P-V



(a) (b)

Figure 5: Experimental and modeling curves for an irradiance level of 960 W/m^2 (a) I-V (b) P-V

Table 2: Variation of the shunt and the series resistances with temperature and irradiance levels (with and without Air-cooling).

T in °C	25			55		
G in W/m^2	960	860	650	960	860	650
RMS error	0.017	0.022	0.091	0.053	0.018	0.087
R_s in mΩ	68.112	75.834	81.439	68.202	75.933	81.546
R_{sh} in Ω	1272.55	4504.12	5554.51	1270.01	4493.45	5539.88

The results presented in table 2 show clearly an acceptable correlation between the model and experimental results. The RMS error values are quite comparable to those obtained in [25]. The series resistance increases with temperature at the same solar radiation, while the shunt resistance decreases, which is an expected behavior of the PV module

Referring to equation (2), an increase in the irradiance will lead to an increase in the surface temperature of the PV module. This behavior will have a weak impact on both series and shunt resistances. This effect is expressed by an increase of the series and decrease of the shunt resistances as shown in Table 2. Thus, this drawback will negatively affect the net output power of the PV module due to the increase in power losses of both resistances. From figure 3.b, 8.5% of the PV panel's power lost when the temperature rises from 25°C to 55°C at a constant irradiance of $650\ W/m^2$. The same conditions are presented for 860 and $960\ W/m^2$ in figure 4.b and 5.b respectively.

5. CONCLUSION

In this paper, the variations of series and shunt resistances of PV modules with temperature and solar radiation have been discussed. The tool, "MY PV TOOL" developed in this work, can be used to accurately determine the series and shunt resistances of a given module when needed. However, measurements (obtaining the I-V and/or P-V characteristics) of the PV module should be made prior to using the tool. Having an idea about R_s and R_{sh} of the PV module may help in figuring out the optimal connection of PV modules to obtain a desired current at a specific voltage.

Table 3: List of symbols

Symbol	Definition
I	Cell output current, in A
I_{ph}	The Photocurrent, is the current produced by the incident light and function of irradiation level and junction temperature, in A
I_{DIODE}	The diode current modeled by the equation for a Shockley diode, in A
I_0	The saturated reverse current or leakage current, in A
q	Electron charge = 1.602×10^{-19} in C.
k	Boltzmann constant = 1.38×10^{-23} in J/k
V	Cell output voltage, in V
T_o	Cell operating temperature, in k
A	The diode ideality factor, in this paper A=1 which represents that the recombination is limited by minority carrier.
R_s	Series resistance of the cell, in Ω
R_{sh}	Shunt resistance of the cell, in Ω
V_T	Thermal voltage, in V
N_s	Number of series cells
I_{phr}	The photon current under standard conditions at Tref & Gref, in A
I_{0r}	Reverse saturation current at reference temperature at Tref, in A
G	The intensity of solar irradiance, in W/m2
G_{ref}	The reference intensity of solar irradiance = 1000 in W/m^2
K_i	Temperature coefficient of the short circuit current
K_0	Temperature coefficient of the open circuit voltage
T_{surf}	Surface temperature of the PV cell
T_{ref}	Reference cell operating temperature= 25°C = 298 k
E_g	Band-gap of the semiconductor material
$I_{scr,cell}$	Short circuit current of PV cell under standard conditions at T_{ref} & G_{ref}, in A
$V_{ocr,cell}$	Open circuit voltage of PV cell under standard conditions at T_r& G_{ref}, in V
$I_{sc,cell}$	Short circuit current of PV cell under operating conditions at T_{surf}& G, in A
$V_{oc,cell}$	Open circuit voltage of PV cell under operating conditions at T_{surf}& G, in V
FF_{SH}	Fill factor which is influenced by the shunt resistance
FF_S	Fill factor that depends on the series resistance
FF_0	Fill factor that is independent of series resistance
FF	Fill factor of the cell which is affected by both resistances
$R_{CH} = \frac{V_{OC}}{I_{SC}}$	Characteristic resistance
$r_S = \frac{R_S}{R_{CH}}$	Normalized series resistance
$r_{SH} = \frac{R_{SH}}{R_{CH}}$	Normalized shunt resistance
Pr	Prandtl number
Re	Reynolds number
Q_{conv}	Rate of convection heat transfer
h	Convective heat transfer coefficient
T_{fluid}	The fluid temperature of the air stream
V_{el}	Velocity of the air stream
v	Viscosity of the air stream
L	Length of the module.
Nu	Average Nusselt number
K_{cond}	Conductivity coefficient of the module

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