The Solar Panel's Performance Dependence on Incident Radiation Intensity and its Surface Temperature

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Abstract: The effect of radiation intensity and temperature on the performance parameters of a solar panel is investigated experimentally using an indoor experimental setup, designed and constructed locally at Higher Institute for Applied Sciences and Technology, Damascus. The experiments have been carried out under various intensity levels of radiation in the range of 700- 2000W/m^2. The experimental results indicate that, radiation intensity has a dominant effect on current parameters. It is found that photocurrent; short circuit current and maximum current have been increased linearly with increasing radiation intensity. So, concentrating system may be regarded as a best choice to enhance the power output of solar system. The power density of the solar panel at 30^{o}C increased from 1.86 mW/cm^2 at 1300W/m^2 to 3.59 mW/cm^2 at 2000W/m^2. The role of temperature on the electric parameters of solar panel is also considered. The practical local possible solar panel's temperature was considered to be in the range of 10–70^{o}C. The experiments cover this temperature range. Experimental results show that all electrical parameters of solar panel such as maximum output power, open circuit voltage, short circuit current, efficiency and fill factor have changed with temperature variation. As well as the amount of changes in these parameters in terms of temperature value have been obtained. According to results, the most significant is the temperature dependence of the voltage which decreases with increasing temperature while the current of the solar panel slightly increases by temperature. On the other hand, it has been observed that solar panel's temperature has a dramatic effect on voltage parameters. Open circuit voltage and maximum voltage are decrease with increasing solar panel's temperature. So, the maximum power density of the mono-crystalline and poly-crystalline silicon solar module decreased from 43.4 and 48.76/cm^2 to 36.32 and 41.88mW/cm^2 for temperature 10^{o}C and 70^{o}C respectively. When testing the effect of temperature on French Photo watt solar cells, obtained 20 years ago and encapsulated in a solar panel locally, in the temperature range of 10–90^{o}C, it was found that, the open circuit voltage decreases by 1.87mV/ ^{o}C which is equivalent to 0.3% of the nominal value. The short circuit current intensity decreases by 20mA/^{o}C which is equivalent to 1% of the nominal value. When comparing these values with those of the company presented at its electronic cite, I_{sc} = +0,06%/°C; V_{oc} = -0,34%/°C, one can conclude that aging effect is important on short circuit current intensity.

Keywords: I-V Characteristics, maximum output power, panel's temperature, radiation intensity.

1. INTRODUCTION

The resources are limited and our dependence on fossil is close to its end. Solar energy could be a good choice of power generation, since the cost of solar panels decreasing rapidly in the past few years. Solar energy is available in abundance in nature and it is considered as one of the easiest and cleanest means of source among all other available renewable energy sources. The energy of sun i.e. solar radiation is converted in to electricity by means of photovoltaic effect. Photovoltaic power generation is a method of producing electricity using solar cell. A solar cell converts incoming solar energy in to electrical energy. The photovoltaic (PV) module consists of number of solar cells. A PV panel consists of number of PV modules. The efficiency of solar photovoltaic system mainly depends on incoming sunlight which falling on the PV panel surface. If the amount of incoming sun light falling on PV panel surface increases the efficiency of PV system also increases and vice versa. Photovoltaic systems have been installed to provide electricity to the billions of people that do not have access tomains electricity. Power supply to remoter houses or villages, irrigation and water supply are important application of photovoltaics for many years to come. In Syria during the last decade, PV solar energy system has shown its huge potential. The amount of installed PV power has rapidly increased especially in the country and North part of Syria.

Silicon based solar photovoltaic (PV) technology is emerging as a potential renewable energy source for future power requirements. Still the cost reduction of this technology is an important area of concern. There are several ways by which the cost of this technology can be reduced, e.g., improving the efficiency, efficient light trapping, using thinner wafer, thin-film silicon technology, concentrator photovoltaic technology, etc. Compared to non-concentrating solar PV systems, the required area for solar PV module is reduced by the factor of concentration ratio, providing significant reduction in the overall cost of solar PV system [1].

The characteristic properties of Photovoltaic (PV) modules are always reported at Standard Test Conditions (STC), irradiance 1000W/m^2, 25^{o}C cell temperature, and AM 1.5 solar spectrum, which are not

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normal working conditions. Accurate knowledge of solar module performance parameters at Standard Test Conditions (STC) from the measured I–V characteristics is very important for the quality control and the performance assessment of solar system. Therefore, it is significant to evaluate the I-V curves of solar module under various environmental conditions. In this context, it is reasonable to focus attention mainly on the analysis of the various factors which are responsible for affecting the performance of a solar PV system. However, the performance is judged on the basis of the power output from the panel, so the analysis should be done for the factors which directly or indirectly affect the power output of solar PV systems.

However, several researchers have correlated the effect of the increase of temperature and irradiance, with their electrical properties from experiments performed in sure environmental conditions using a sun simulator [2]. In such experiments, some of the parameters can be kept constant, while this is not possible in a natural environment, where a number of micro-climatic parameters simultaneously with the temperature and the irradiance significantly influence the module performance. It has been reported that simulations with STC data can lead to an overestimation of the produced power as much as 40%. It is thus important that experimental data are used together with the site particular meteorological data as input in simulation models in order to calculate the energy production of different PV generators. The accurate parameters introduced in the simulations are very important to provide reliable results for the productivity of PV generators and facilitate the selection of the most appropriate module type for a specified application at a selected site improving in the same time the economic attractiveness of PV power supply system [3]. Moreover, accurate knowledge of solar module performance parameters from the measured I–V characteristics is very important for the quality control and the performance assessment of solar system. Therefore, it is significant to evaluate the I-V curves of solar module under various environmental conditions. In this context, it is reasonable to focus attention mainly on the analysis of the various factors which are responsible for affecting the performance of a solar PV system. However, the performance is judged on the basis of the power output from the panel, so the analysis should be done for the factors which directly or indirectly affect the power output of solar PV systems.

For this purpose, some research groups have studied the photovoltaic module performance under outdoor conditions, focusing on the temperature and the solar radiation influence on their properties. The cell/module operating temperature, T_c, acts essentially in the photovoltaic conversion process, affecting electrical power output. The efficiency of the PV module strongly decreases almost linearly with Tc. Simple characteristic equations for the PV operating temperature have been proposed involving several parameters [4]. Temperature coefficients have been calculated theoretically expressing the change in the performance of the modules as a function of the working temperature with reference to their values at STC [5]. In addition, practical relations for the average cell temperature per month and performance ratio of PV arrays have also been reported [6]. It has been referred that at the operating temperature of 64^{o}C, there was a decrease of 69% in the efficiency of the solar cell compared with that measured at STC [7]. With the temperature increase of the silicon PV modules as a function of illumination time, a decrease of the output power (-0.65%/K), of the fill factor (FF) (-0.2%/K), and of the conversion efficiency (-0.08%/K) has been observed [8]. On the other hand, the evolution of the cell performance with the irradiance showed that the efficiency of the cells is reduced at a rate different from the reduction of sunlight density. Efficiency curves versus irradiance at constant cell temperature showed maxima at irradiances lower than at STC irradiance of 1000W/m^2, while proposing that further research and advanced physical modeling of cells and modules would help to understand this behavior. The consequence is that the reliability of PV modules, as they are actually designed to operate under any climate conditions and in any location, may significantly vary between different types of climate. There are other parameters that influence the panel IV characteristics such as dust shading, ambient temperature, panel tilt angle and orientation.

As the characteristic properties of Photovoltaic (PV) modules are always reported at STC, the present work provide an experimental methodology for measuring the influence, of panel's temperature and incident radiation intensity on its surface, on the IV characteristics of this panel such as short circuit current intensity, open circuit voltage, maximum power, fill factor and conversion efficiency.

2. THEORY

Silicon solar cell is basically a p–n junction which generates a DC current intensity when exposing to light. The steady state current–voltage (IV) characteristics of a silicon p–n junction module is often described based on one diode model as given in the following equation:

$$I_{pv} = I_L - I_D\{\exp[(q(V_{pv} + I_{pv}R_s)/(A*K*T))] - 1\} - (V_{pv} + I_{pv}R_s)/R_{sh} \quad (1)$$

$$P_{pv} = V_{pv} * I_{pv} \quad (2)$$

where I_{pv} is the generated current density by solar panel, I_L is the light generated current density, I_D is the reverse saturation current density or dark current density, q is the elementary charge ($1.6x10^{-19}$ Coulomb), V_{pv} is the measured solar panel voltage, k is the Boltzmann's constant ($1.38x10^{-23}$ J/K), A is the ideality factor of non-ideal diode, T is the temperature in Kelvin, R_s is the series resistance and R_p is the parallel or shunt resistance. These parameters have a dominant impact on the shape of IV characteristics of the solar cell at any given light intensity and solar cell temperature.

Ideally, in a solar PV module, lower series resistance and very high shunt resistance are required for higher power generation. In solar PV modules, the PV cells are generally connected in series in order to obtain adequate working voltage. The solar PV modules can be arranged in series-parallel combination to make an array, which produces desired power. Thus, when dealing with a solar module of N_s cell in series and of N_p cell in parallel, the terminal equation for current and voltage of the solar PV array as described by Veerachary *et al*. [9], Veerachary and Shinoy [10], Kim and Youn [11] and Kim *et al*. [12] takes the form:

$$I_{pv} = N_pI_L - N_sI_D\{exp[q(V_{pv}/N_s + I_{pv}R_s/N_p)/(AkT)] - 1\} - (N_pV_{pv}/N_s + I_{pv}R_s/N_p)/R_p \quad (3)$$

The simplified circuit used for the quantitative study of the solar cell electrical characteristics considers an ideal behavior of the solar cell based on an ideal current source that is controlled only by the ideal diode (see Figure **1**). I_p is the diode current. This model is sufficient for several applications. However, it is highly inaccurate to estimate the maximum power delivered by the solar cell at low and average irradiation. Especially, the use of the model at low irradiation can lead to negative values of R_s, while at higher irradiation up to one sun gives significantly different values. Therefore, major errors of this model may be due to the series resistance losses, in addition to the shunt resistive losses, which are related to the quality of the solar cell material, plus to the real fill factor. The latter parameter decreases with the increase in R_s, [13,14] and with the decrease in R_p [15].

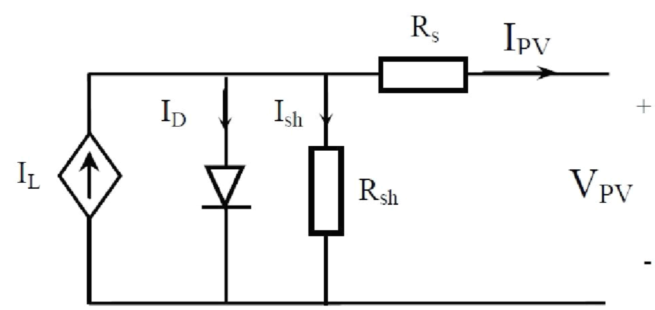

Figure 1: Equivalent circuit of a solar cell.

The performance of the solar module, characterized by the values of the short circuit current density (I_{sc}), open circuit voltage (V_{oc}), fill factor (FF) and efficiency (η) of the solar module [16] can be determined. The large values of I_{sc} give the maximum power generated by solar module. The open circuit voltage (V_{oc}) occurs when there is no current passing through the module, i.e. V (at I=0). Large Voc gives the maximum power generated by solar module and is given by:

$$V_{oc} = (kT/q)\ln(I_{PV}/I_D + 1)) \quad (4)$$

Fill factor (FF) is a measure for the quality of the solar module. It is the ratio of maximum power density ($P_m=I_mV_m$) to the theoretical maximum power density ($P_{th}=I_{SC}\ V_{OC}$). I_m and V_m are the maximum power density corresponded values of current density and voltage. Large FF means maximum power generated by solar module:

$$FF = P_m/P_{th} = (I_mV_m)/(I_{sc}V_{oc}) \quad (5)$$

Efficiency (η) is the ratio of the electrical output power (P_{out}) compared to the solar input power (P_{in}=G.a). G being the solar radiation intensity and ais the solar panel area. Efficiency is related by I_{sc}, V_{oc} and FF;

$$\eta = P_{out}/(G.a) = (FFI_{sc}V_{oc})/G.a \quad (6)$$

In real modules power is dissipated through the resistance of the contacts and through leakage currents around the sides of the device. These effects are equivalent electrically to two parasitic resistances in series and in parallel with the equivalent circuit of solar module. For an ideal module, R_{sh} would be infinite and would not provide an alternate path for current to flow, while R_s would be zero, resulting in no further voltage drop before the load [17]. Most of silicon solar modules are designed to work under normal sunlight and their performances are evaluated at 25^{o}C under an air mass (AM) 1.5 and solar irradiation intensity of 1 Sun.

3. EXPERIMENTAL SETUP

A measuring system is presented for indoor testing of solar cells and modules under different operating conditions of cell temperature and radiation intensity on its surface. In the experimental setup, see Figure **2**, a controlled radiation source of maximum 150W power, connected to a DC power supply, is used. The radiation source allows changing the radiation intensity in the range of 200W/m^2 to 2000W/m^2. Kipp and Zonenpyranometer (global solar radiation) which is a radiometer designed for measuring the global irradiance on a plane surface resulting from radiant fluxes in the wave length range from 300 nanometers (nm), or less, to 2800nm (see Figure **3**). The received radiation is converted to heat by the blackened surface. The temperature difference between the surface and the body of the instrument is proportional of the irradiance of the global solar radiation; it is measured by a thermopile consisting of several thermocouples connected in series. Photowatt's mono-crystalline silicone solar cell (see Figure **4**) is encapsulated locally on a cupper base for forming a one-cell solar panel of thermal conductive base (see Figure **5**). A water bath

Figure 2: Experimental setup.

Figure 3: Kipp and Zonenpyranometer.

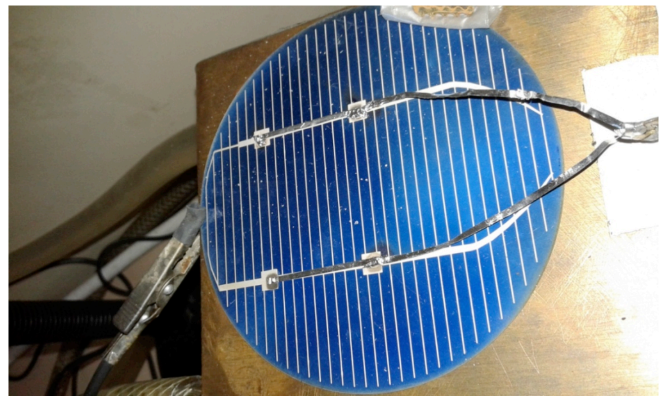

Figure 4: The used Photowatt's solar cell.

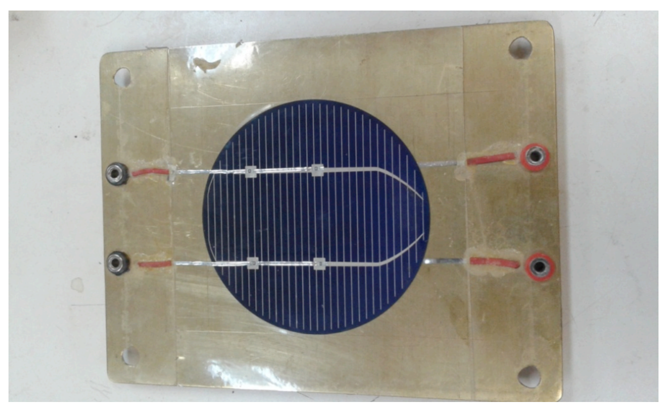

Figure 5: The encapsulated solar panel.

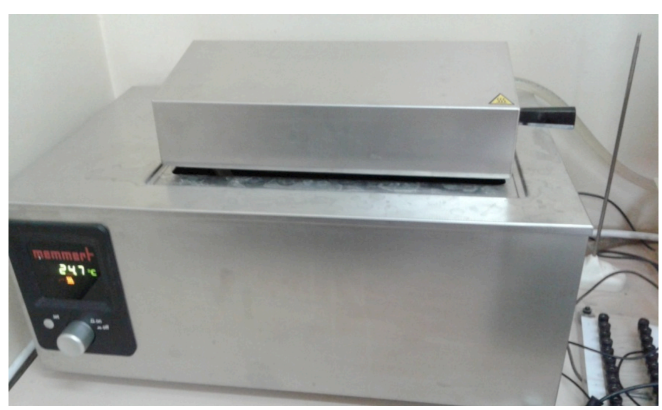

Figure 6: The used thermal bath.

(see Figure **6**) is used to control the solar panel's temperature in the temperature range of 10°C to 90°C. Current-voltage curves are acquired in the range of irradiance from 200 W/m^2 to 2000 W/m^2. The maximum power point (mpp), panel's efficiency and fill factor are normally detected on-line.

4. EXPERIMENTAL RESULTS

4.1. Panel's Performance Dependence on Panel's Surface Temperature

When measuring the surface temperature effect on the performance of the studied solar panel at radiation intensity of 1300 W/m^2, the results presented on Figures **7** to **13** were obtained. Figures **7** and **8** show the IV characteristics, of the studied panel, and the

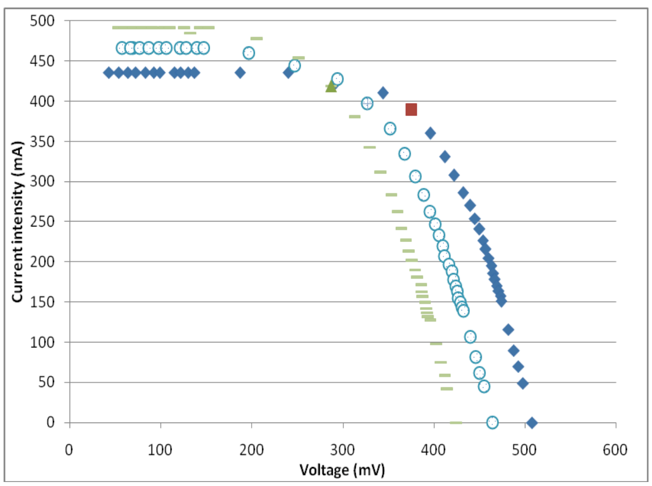

Figure 7: Panel's IV characteristics at 1300W/m^2 radiation intensity and 30°C (♦), 50°C (○) and 70°C (-). Different symbol on each curve represent the corresponded maximum power point.

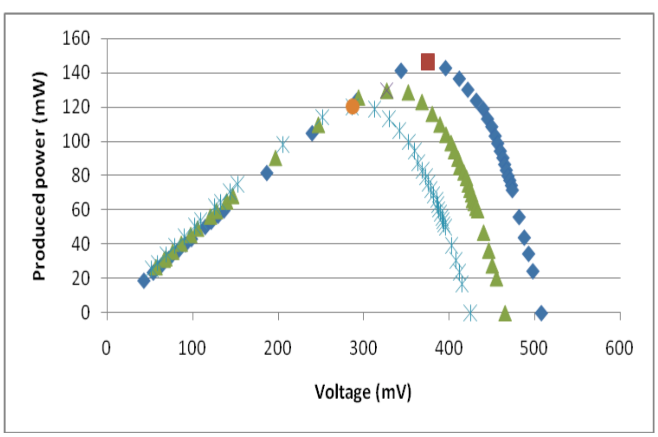

Figure 8: Panel's produced power at 1300W/m^2 radiation intensity and 30°C (♦),50°C (▲) and 70°C (ж). Different symbol on each curve represent the corresponded maximum power point.

produced by it power, at 1300 W/m^2 and different solar panel's temperature respectively. Figure **9** shows the temperature dependence of the panel's I_{sc} and I_m while Figure **10** gives the temperature dependence of V_{oc}. Figures **11** to **13** give the temperature dependence for P_{max}, FF and η respectively.

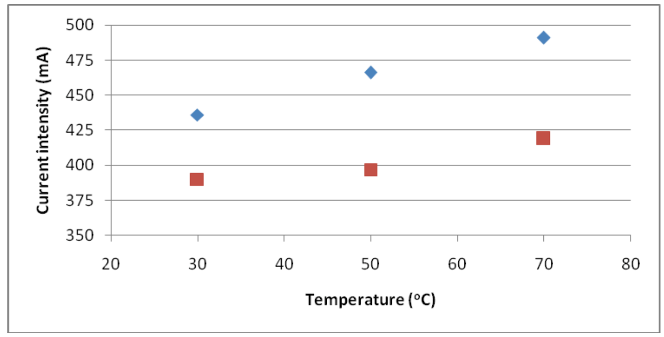

Figure 9: Temperature dependence of panel's I_{sc} (♦) and I_m (■) at 1300W/m^2 radiation intensity.

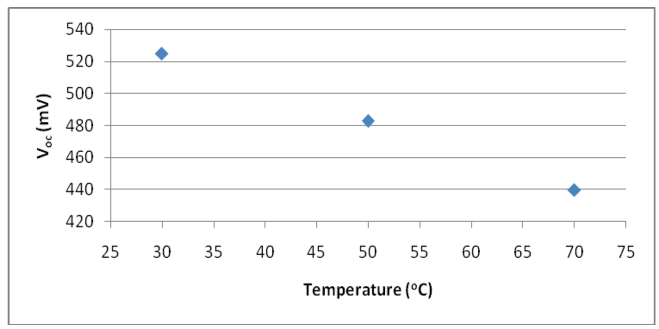

Figure 10: Temperature dependence of panel's V_{oc} (♦) at 1300W/m^2 radiation intensity.

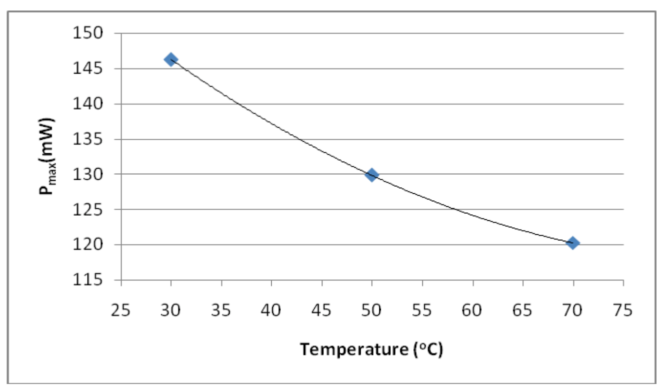

Figure 11: The temperature dependence of panel's P_m (♦) at 1300W/m^2 radiation intensity.

It is seen from Figure **9** that, I_{sc} could be approximated as a linear function of temperature. The increment in I_{sc} is 1.375mA/°C while the decrease in V_{oc}, see Figure **10**, is 2.075 mV/°C or 0.42%. The obtained result coincides well with that of [18] which reveals that for every 1K increase in surface temperature the reduction in open circuit voltage was 0.45%. Thus, as the temperature of PV cell increases its open circuit voltage (Figure **10**), maximum produced power (Figure **11**), FF (Figure **12**) and conversion efficiency (Figure **13**) decrease. Moreover, the increment in I_{cs} is small due to rise in temperature. Hence, the performance of PV panel reduces due to rise in its surface temperature.

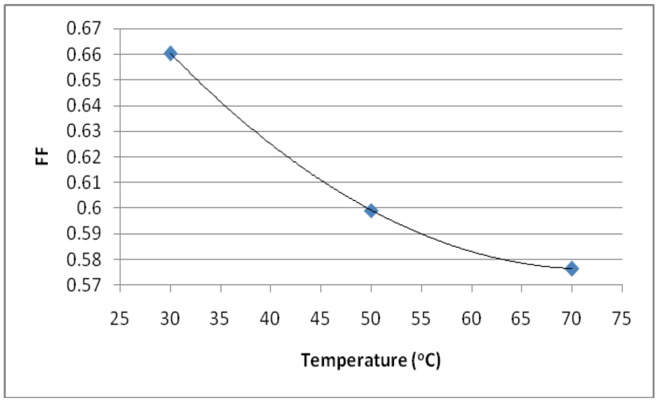

Figure 12: The temperature dependence of panel's FF (♦) at 1300W/m^2 radiation intensity.

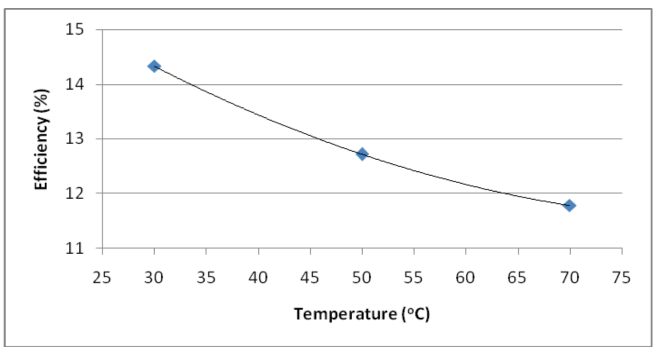

Figure 13: Panel's efficiency (♦) temperature dependence at 1300W/m^2 radiation intensity.

Experimental results showed that the most significant changed by temperature is voltage which decreases with increasing temperature while I_{sc} slightly increase by temperature. Reduction in the V_{oc} for silicon solar cells is about 2mV/°C. The obtained experimental results with regard to V_{oc} agree well with those of [19, 20, 21]. The influence of panel's temperature is also important on panel's maximum produced power (0.65mW/^{o}C). The temperature dependence of maximum produced power P_m, current density I_m, panel's efficiency η fill factor FF and $P^*=P_m/a$ could be approximated as a polynomial function of second order over the studied temperature interval:

$$Panelelectricproperty = a_1T^2 + a_2T + a_1 \quad (7)$$

where the panel's surface temperature T is expressed in ^{o}C. The coefficients of the polynomial functions are given in Table **1**.

Table 1: Coefficients of the Polynomial Functions (7)

Characteristic	$a_1(10^{-4})$	a_2	a_3
P_m (mW)	88	-1.508	183.77
I_{sc} (mA)	-62	2	381.63
I_m (mA)	187	-1.15	407.63
FF	0.5	-0.007	0.8241
η (%)	8	-0.148	18.008
P^* (mW/cm^2)	1	-0.019	2.341

In accordance with [22] the experimental results of the present work show that, the increment in the panel's temperature by 40ºC leads to 17.77% of energy loss in the PV module. This loss becomes 11.23% when the panel's temperature increases by 20ºC.

4.2. Panel's Performance Dependence on Radiation Intensity

When measuring the radiation intensity effect on the performance of the studied solar panel at constant temperature 40^{o}C, the results presented on Figures **14** to **20** were obtained. It is found that, in accordance with [23] irradiance has a large effect on short-circuit current, i.e. the relatively horizontal arm of the IV curve, while the effect on open- circuit voltage, i.e. the relatively vertical arm of the curve, is rather weak. Figures **14** and **15** show the IV characteristics, of the studied panel, and the produced by it power, at surface temperature of 40^{o}C and different solar radiation intensity levels and the produced by it power, at surface temperature of 40^{o}C and different solar radiation intensity levels respectively.

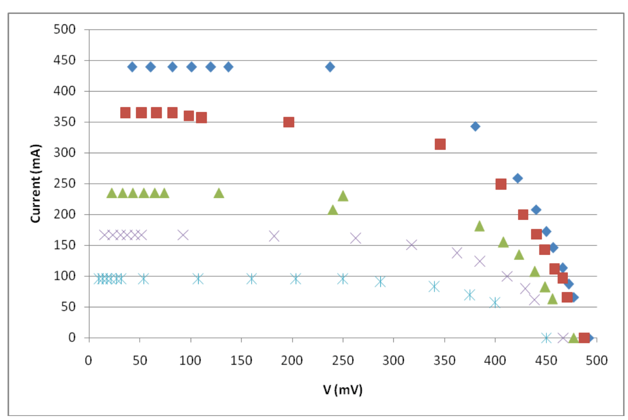

Figure 14: The studied panel IV characteristics atsurface temperature of 40^{o}C and radiation intensity of 2000W/m^2(♦),1700W/m^2(■), 1300W/m^2(▲),1000W/m^2(x) and 700W/m^2(ж).

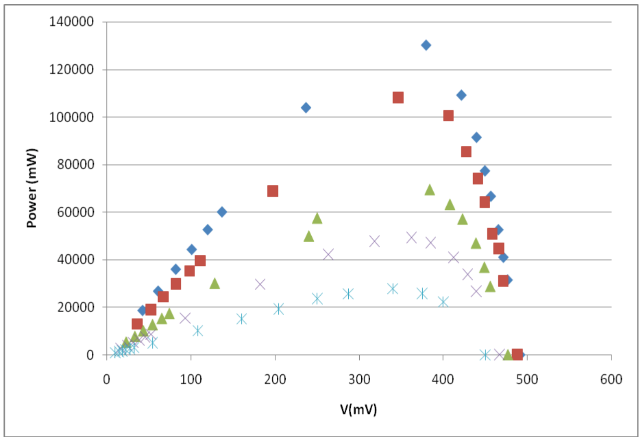

Figure 15: The produced power by the studied panel atsurface temperature of 40°C and radiation intensity of 2000W/m^2(♦), 1700W/m^2(■), 1300W/m^2(▲), 1000W/m^2(x) and 700W/m^2(ж).

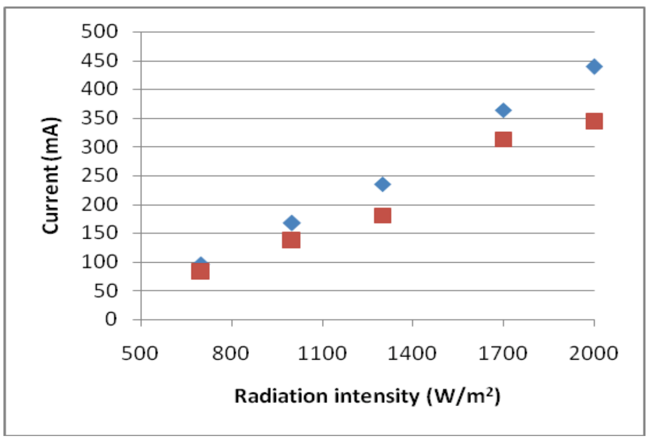

Figure 16: Panel's I_{sc} (♦) and I_m (■) dependence on the radiation intensity at surface temperature of 40°C.

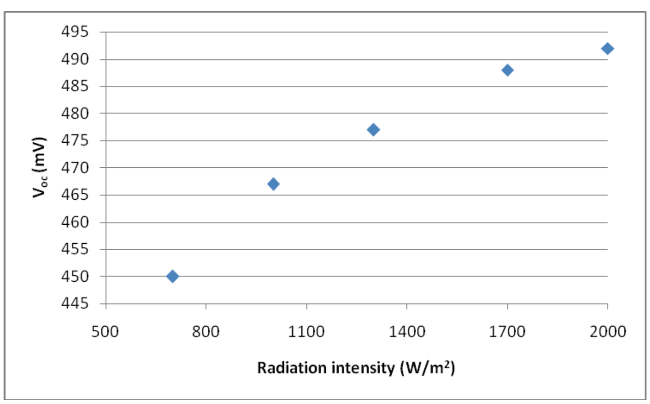

Figure 17: The radiation intensity dependence of panel's V_{oc} (■) at surface temperature of 40°C.

Figure **16** shows the radiation intensity dependence of the panel's I_{sc} and I_m while Figure **17** gives the radiation intensity dependence of V_{oc}. Figures **18** to **19** give the radiation intensity dependence for P_{max}, FF and η respectively. It is seen from Figure **16** that, I_{sc} could be approximated as a linear function of radiation intensity. The increment in I_{sc} is 0.265mA/(W/m^2) while the increment in V_{oc} is 0.01385 mV/(W/m^2). On the other hand, it is observed that, the increment in P_{max} is 0.0788mW/(W/m^2) while the decrease in FF is negligible [3.75x10^{-5} (W/m^2)$^{-1}$]. The increment in the panel efficiency is remarkable [6.208x10^{-3} (W/m^2)$^{-1}$]. Therefore, concentrating system may be regarded as a best choice to enhance the power output of solar system.

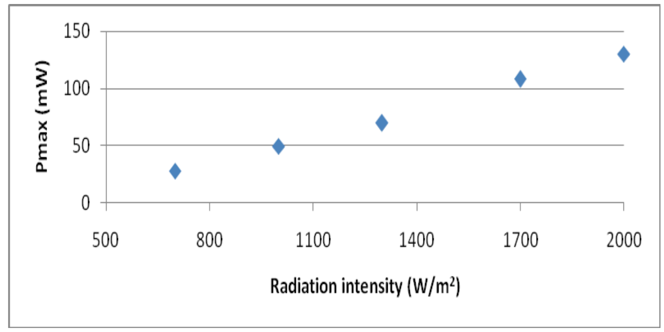

Figure 18: The radiation intensity dependence of panel's P_{max} (♦) at surface temperature of 40°C.

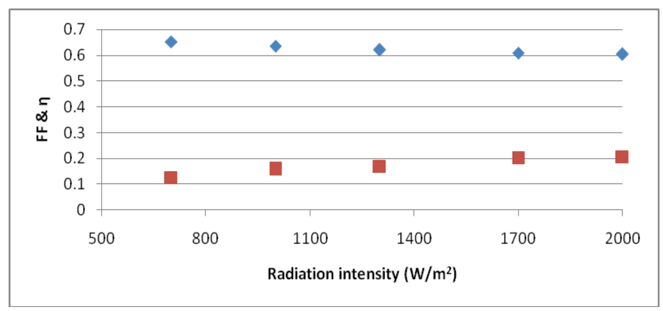

Figure 19: The radiation intensity dependence of panel's η(■) and FF (♦) at surface temperature of 40°C.

Finally, it is found that, the radiation intensity dependence of P_{max}, I_m, η, FF and P* could be approximated as a polynomial function of second order over the studied radiation intensity level interval:

Table 2: Coefficients of the Polynomial Functions (8)

Characteristic	b_1	b_2	b_3
P_{max} (mW)	35.06	0.0575	26.745
I_{sc} (mA)	55.05	0.2905	-55.67
V_{oc} (mV)	-25.05	0.0544	400.93
FF	25.03	-25.03	0.7073
η (%)	-35.05	0.0135	4.694
P^* (mW/cm^2)	15.07	0.0007	0.2152

$$Panelelectricproperty = b_1G^2 + b_2G + b_1 \quad (8)$$

where the radiation intensity G is expressed in W/m^2. The coefficients of the polynomial functions (8) are given in Table **2**.

CONCLUSIONS

In this work, we have studied the behavior of silicon solar panel under the variation of the temperature and incident radiation intensity level. The electrical properties of the panel are studied by varying its surface temperature in the range between 10 and 70°C. These properties are also studied for a varying incident radiation intensity level in the range between 700 and 2000W/m^2. We have shown that:

- The increase in temperature causes the reduction of the open circuit voltage V_{oc}, the produced maximum power P_{max}, the fill factor FF and the conversion efficiency η of the solar panel.
- The decrement in open circuit voltage is 2.075 mV/^{o}C or 0.42%.
- The concentrating system may be regarded as a best choice to enhance the power output of solar PV system.
- The short circuit current I_{sc} increases with temperature by 1.375mA/^{o}C.
- The increase in the radiation intensity causes the increment of short circuit current I_{sc}, the open circuit voltage V_{oc}, the produced maximum power P_m, and the conversion efficiency η of the solar panel.
- The decrement in the fill factor FF is observed.
- The experimental results obtained in this work coincide well with available in literature results (see for example [24]).

The obtained results are useful for a full understanding of temperature and radiation intensity dependences of silicon solar panels and contribute to the design and installation of the solar panels.

ACKNOWLEDGEMENTS

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NOMENCLATURE

- A Ideality factor of non-ideal diode
- a Solar panel area (cm^2)
- AM Air mass
- DC Direct current (mA)
- FF Fill factor
- G Radiation intensity (W/m^2)
- I_D Reverse saturation current density or dark current density (mA)
- I_L Light generated current density (mA)
- I_m Maximum power current density value (mA)
- I_{pv} Generated current density by solar panel (mA)
- I_{sc} Short circuit current density value (mA)
- k Boltzmann's constant (1.38x10^{-23}J/K)
- N_p Number of PV cells in parallel
- N_s Number of cells in series
- P_{in} Input power (mW)
- P_m Maximum power density (mW)
- P_{out} Output power (mW)
- P_{th} theoretical maximum power density (mW)
- PV Photovoltaic
- q Elementary charge (1.6x10^{-19} Coulomb)
- R_p Parallel or shunt resistance R_{sh}.
- R_s Series resistance
- STC Standard Test Conditions
- T Temperature (K)
- T_c Cell or panel surface temperature (^{o}C)
- V_m Maximum power voltage value (mV)
- V_{oc} Open circuit voltage value (mV)
- V_{pv} Measured solar panel voltage (mV)
- η Panel or cell efficiency

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