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Modeling of a High Performance Grid Connected Photovoltaic System

Ali Salameh Khraiwish Dalabeeh[1*] and Anwar AL-Mofleh[1*]

[1]*Department of Electrical Engineering, Faculty of Engineering Technology, Al-Balqa' Applied University Amman, Jordan Amman, P.O.Box (15008), Marka Ashamalia, Jordan.*

Authors' contributions

This work was carried out in collaboration among both authors. Both Authors read and approved the final manuscript.

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ABSTRACT

This paper presents detailed modelling of a grid-connected photovoltaic (PV) system components. The study is helpful to understand the working principles of the PV system. The performance of the system has been discussed by means of a Matlab/Simulink Toolbox. The results show that the PV system capable of tracking the maximum power point (MPP) quickly and precisely in case of sudden changes in solar radiation, cell temperature, and in case of existence of sand. Under the non-uniform atmospheric conditions, to get a high performance of the PV system, appropriate converters are required to operate at the MPP.

Keywords: Photovoltaic system; solar irradiation; Maximum Power Point Tracking (MPPT).

**Corresponding author: E-mail: alidalabeeh@yahoo.com, alidalabeeh@yahoo.com;*

1. INTRODUCTION

Solar energy provides the opportunity to develop electric energy from clean, endless, and green energies [1,2]. A PV cell is a basic unit that generates voltage in the range of 0.5 to 0.8 volts depending on cell technology being used [3,4]. Therefore the solar cells are connected in series and parallel in order to create a solar module depending on the capacity demands [5]. Regardless of the intermittency of sunlight, solar energy is widely available and completely free of cost [6-8]. The efficiency of the PV cells is quite dependent to the environmental and operational conditions. The output power of the PV systems affected by solar radiation, ambient temperature, and sand (dust, clouds, shading, etc.) [9,10]. The cell conversion ranges from 12% up to a maximum of 29% for very expensive units [11,12]. So to extract the maximum possible power from a PV system, tracking the single maximum power operating point is very important to raise the efficient operation of the PV system, and so, MPPT is one of the most important issues in PV system [13,14]. MPPT methods are various and they differ in terms of complexity, speed of response, and cost [15,16,17,18,19]. A popular method of perturb and observe (P&Q) based on a boost converter as MPPT device is considered in this paper.

In the last few years, the demand for electrical power in Jordan has increased significantly due to developments in the industrial sector and people's standard of living conditions. Solar energy can cover these conditions in the future, and achieve great results due to the location of the Kingdome and the large desert areas. The demand for solar energy, globally, has increased by 20% to 25% over the past 20 years [20]. The electrical system powered by solar arrays requires special design considerations due to the varying nature of the solar power generated resulting from unpredictable and sudden changes in weather conditions, which change the solar radiation level as well as the cell operating temperature. A PV array is interfaced with DC/DC converter to obtain the desired DC voltage by utilizing Maximum Power Point Tracking (MPPT) technique to extract the maximum power, which is converted to alternating current (AC) by an inverter.

The nonlinear output PV characteristics, Power-Voltage (P-V) and Current-Voltage (I-V), are affected by the solar radiation and the temperature. The PV system should always operate so as to extract the maximum power under the variations of solar radiation, while the environment temperature supposed to be maintained at nominal value (250C), therefore the PV current only depends on solar radiation. The time, required, to reach MPP under variable conditions has to be analysed to evaluate the performance of the PV system [21,22].

2. PHOTOVOLTAIC SYSTEM MODELLING

2.1 PV Cell Model

A mathematical description of current - voltage terminal characteristics for PV cells is available in the literature. The single exponential equation (1) which models a PV cell is derived from the physics of the PN junction and is generally accepted as reflecting the characteristic behavior of the cell [7].

$$I = Iph - Is\left\{exp\frac{q(V+RsI)}{NKT} - 1\right\} - \frac{(V+RsI}{Rsh} \quad (1)$$

Where:

I_{ph}: Represents the current generated by the photons (it will be constant if the radiation and the temperature are constants too). The photon generated current will flow out of the cell as a short-circuit current (I_{sc}) .
I_s : Is the panel dark saturation current, in A, which depends strongly on temperature
q: Is the electron charge (1.602×10^{-19} C),
V: Is the voltage across the diode (V),
K: Is the Boltzmann's constant (1.381×10^{-23} J/K),
T: Is the working temperature of the cell, in Kelvin.
N: Ideality factor of the diode
R_s: Is the series resistance in ohm, which models the ohmic losses.
R_{sh}: Is the shunt resistance, in ohm, which represents the current leakage.

From the equations, an equivalent circuit can be easily determined, and this aids in the development of the simulation model. This equivalent circuit model is shown in Fig. 1. It includes a current source, a diode, a series resistance and a shunt resistance.

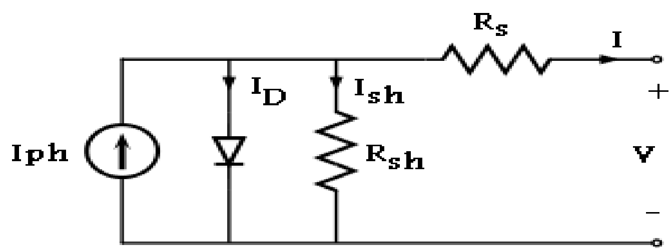

Fig. 1. PV cell equivalent circuit

2.2 The Influence of Solar Irradiation Variation

Based on the above equation, the subsystem of Fig. 1 is obtained. The above model includes two subsystems: one that calculates the PV cell photocurrent which depends on the radiation and the temperature [23].

$$Iph = [Isc + Ki(T - 298)]\frac{G}{1000} \quad (2)$$

Where K_i=0.0017 A/C◦ is the cell's short circuit current temperature coefficient and G is the solar radiation (W/m^2).

2.3 The Influence of Cell Temperature Variation

Like all other semiconductor devices, solar cells are sensitive to temperature, Increase in temperature, reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. Panel temperatures in the summer in warm climates can easily reach 50C° resulting in a 12% reduction in output compared to the rated output at 25C°. To calculate the exact percentage of losses due to the difference of temperature in Jordan, For the PV module selected in section below (Kyroce KD235XL) the temperature confection for voltage is (-1.33×10^{-1} V/C°) and for current is (5.13×10^{-3} A/C°).

The Jordan ambient temperature is about 45C° so it's greater than the STC (standard test conditions) value by 20C°. By calculating the value of the reduction in voltage and current the expected effect of temperature is about 1% of losses in power. The diode reverse saturation current varies as a cubic function of the temperature and it can be expressed as [23]:

$$I_S\ (T)=I_s\ [T/T_{nom}]^3 \exp\ [(T\ /_{T_{nom}} - 1)E_g/(N.V_t\ )] \qquad (3)$$

Where

(I_s) is the panel dark saturation current, in A
T_{nom} is the nominal temperature, equals to 300K
E_g is the band gap energy of the semiconductor
V_t is the thermal voltage.

When there is no connection to the PV cell (open circuit), the photon generated current is shunted internally by the intrinsic p-n junction diode, this gives the open circuit voltage (V_{oc}). In general, for a given solar radiation, when the cell temperature increases, the open circuit voltage V_{oc}, drops slightly, while the short circuit current increases. Figs. 2 and 3 show temperature effect.

2.4 The Influence of Dust and Sands

Dust, Sands, clouds, and snow decrease solar panel efficiency. For our reign in Jordan as Mediterranean climate high altitudes require high tilt in a PV system. A lower fixed tilt angle is recommended to optimize year-round solar. Gain dust generally tends to fall off with the increase in the tilt angle. The reign of Jordan is almost clear and not dusty or windy so the effect of the dust and soil can be reduced when using a fixed (manual change) title angel is about 3-4%.

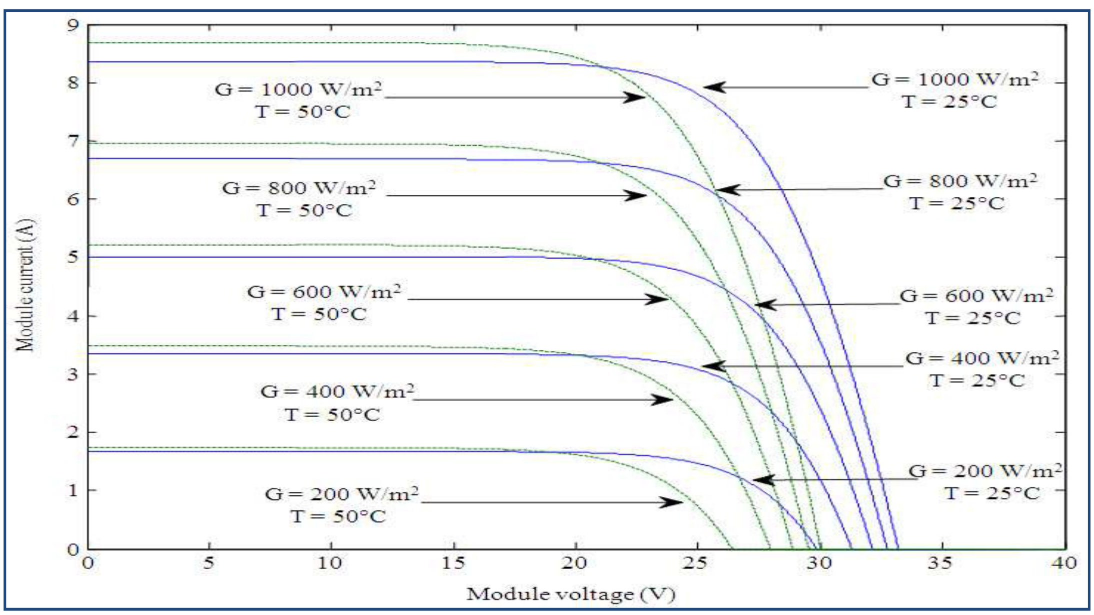

Fig. 2. The I-V characteristic for 25° and 50 C°

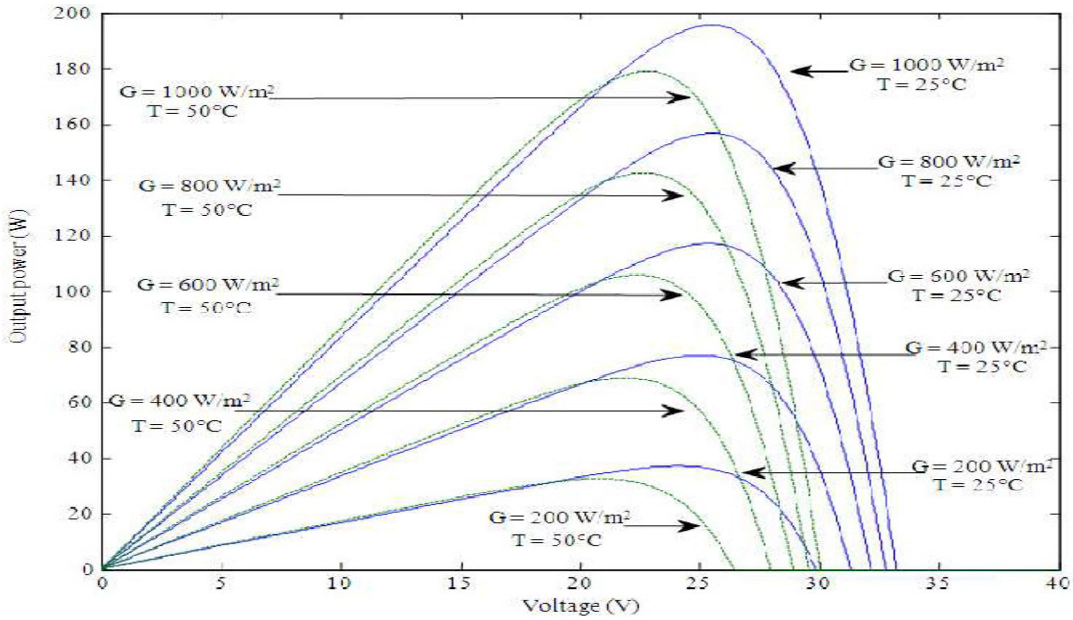

Fig. 3. The P-V characteristic for 25° and 50 C°

2.5 Boost Converter with MPPT Controller and the Voltage Sourced Converter

A DC-DC power, converter boosts the DC power from one voltage level to another higher or lower to the input voltage, has to be added at the output of the photovoltaic array to achieve the optimum voltage and to implement the Maximum Power Point Tracking (MPPT).

$$Vo = {}^{Vin}/_{(1-D)} \tag{4}$$

Where Vin is the input voltage (output voltage of PV array), Vo is the output voltage and D is the duty ratio of controllable switch. With the boost topologies the output voltage could be higher than input voltage. And can vary from 0 to1, although there is no practical value of D equal to 1 due to voltage limitation issues Fig. 4. Is the configuration of the boost circuit and its control system [10]. In the detailed model, the DC-DC converter boosts DC voltage from 273.5 V to 500V. Basically, the module current is perturbed by a small increment, and the resulting change in the power is observed. A simple updating algorithm is given as follows: The terminal voltage V and current I of PV arrays am first measured and PV power P is therefore obtained from the product of V and I If the maximum power point Pm is the demarcation point, when V (k) >V (k-1), if P (k)-P (k-1)>0, then the solar cell work in the left section of the curve. To make the operating point close to the maximum power Pm point, need to continue to increase the output voltage V; In contrast, V (k) >V (k-1), if P (k) -P (k-1) <0, then the solar cell work in the right part of the curve, in order to make the operating point near the point of maximum power Pm, require to reduce the output voltage V. With this control algorithm, the operating point of PV arrays can move toward the maximum power point corresponding to different temperature and irradiance. In order to suit the frequency and voltage level requirement of the load, a suitable switching power inverter is used. PV array is connected to the AC grid via a common DC/AC inverter. The inverter is used in current control method with PWM switching mechanism to make the inductance current track the sinusoidal reference current command closely and obtain a low THD injected current. The direct current (DC) link capacitor maintains the solar PV array voltage at a certain level for the voltage source inverter. The single phase inverter with the output filter converts the DC input voltage into AC sinusoidal voltage by means of appropriate switch signals and then the filter output pass through an isolation step up transformer to set up the filter output voltage required by the electric utility grid and load [24].

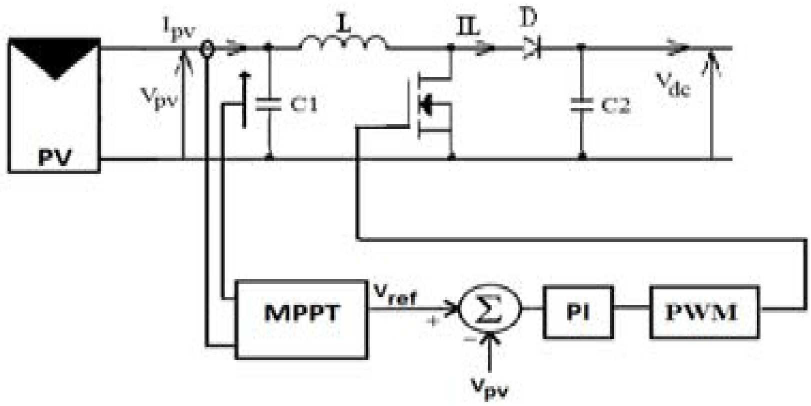

Fig. 4. Boost converter with MPPT controller

3. RESULTS AND DISCUSSION

Fig. 5 shows the system model configuration that will be used to generate electrical energy using PV array, then feed it to a building in Amman (load) as a case study. And the extra power to the grid. The system is composed of two main buses: a DC bus and an AC bus. The PV panels are connected to the DC bus. This power is then converted to AC bus to which the electrical load and the grid will be connected. The annual global solar radiation in Amman-Jordan is about 5.47 kWh/m^2/day. Suppose that the electrical load of the research building is 40 kWh/day. Due to the losses of the system the Electrical load will be El = 1.15 * 40 = 46 kwh/day. The average number of the sunshine of hours in Jordan for the year is set to 9.5 hours per day If the selected PV module is KYOCERA KD235GX solar panel with 235Wp peak power. The parameters of the PV module used in our study are tabulated in Table 1 and its approximated I-V and P-V characteristics are depicted in Figs. 2 and 3 respectively [15]. PV array size = Electric. Load / sunshine hours 46 / 9.5 =4. 85 kW.Due to the inverter losses PV array size becomes: PV array size = 1.045 * 4.85 = 5.07 KW. The number of PV modules = PV array sizing / peak power of module = 5.07/ 0.235 = 22. If the selected Grid Tie Solar Inverter is GT5.0SP with the specifications in Table 2 Inverter power= 4850 * 0.95 = 4651.15 W. So the number of PV in series = 600/36.9 = 16 modules Number of PV modules in parallel = 22/16 = 2 modules. So the final number of PV panels = 2*16 = 32 modules. The maximum current = (number of PV in parallel) * Isc = (2) *8. 55 = (17.1) A. So number of PV in parallel = 22/8.55 = 2 modules Number of PV modules in parallel = 22/2 = 11modules. So the final number of PV panels = 2*11 = 22 modules, and the maximum voltage = number of PV in series * Isc = 11*36.9 = 405V.

The I-V and P-V characteristics for the array and for each module are shown in Figs. 6 and 7, respectively. The duty cycle of the boost is set to 0.5.

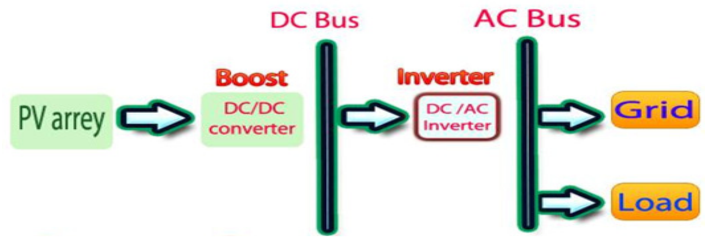

Fig. 5. System model configuration

Table 1. The PV module data

Power peak	235watt
Maximum power voltage V_{mpp}	29.8V
Maximum power current I_{mpp}	7.89A
Open circuit voltage V_{oc}	36.9V
Short circuit current I_{sc}	8.55A
Max system voltage	600V
Temperature voltage coefficient	-1.33*10^{-1} V/C0
Temperature current coefficient	5.13*10^{-3} V/C0

Table 2. The specification of selected inverter

AC power	5000
AC voltage	240V
AC current	21A
Frequency	50Hz
Maximum DC voltage Vmax	600V
Maximum DC current Imax	22A
Maximum efficiency	95%

3.1 The Effect of Irradiation

3.1.1 Irradiation varying in a ramp up/down form

At t=0sec the radiation is set to 1000w/m^2 then at t=0.7 Sec it decreases with a rate of 1500w/m^2/Sec for 0.5sec then at t=1.5sec it increases with a rate of 1500w/m2/search for o. 5sec. As it is shown in Figs. 8 and 9. shows the variation of the PV DC voltage, PV DC current, and the diode current as a result of the radiation variation. Fig. 10 shows the PV output power and the effect of the variation of the radiation. And how the duty cycle decreases to track the PV output power close to the maximum power point of the PV for the given conditions.

3.1.2 Irradiation varying in a step form

At t=0. 7 Sec a step from 1000w/m^2 to a 200w/m^2 has been done as shown in Figs. 11- 13 show the variation of the output array voltage and power. It is shown that the output PV current decreases and increases as the radiation decreases or increases. Once the radiation changes sharply consequently the output PV power changed sharply Fig. 13 shows that the duty cycle value follows the changes of the radiation (the response of the MPPT) in order to track the maximum power point that can be attained from the PV array under these conditions.

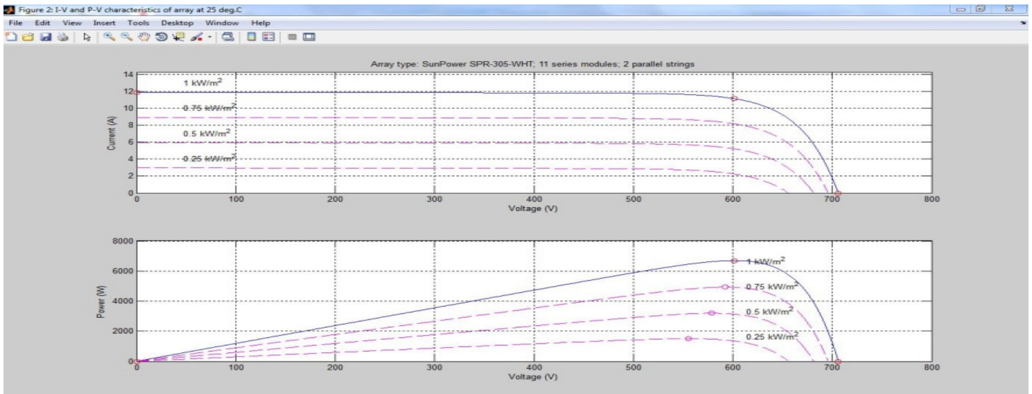

Fig. 6. Array I-V and P-V characteristics

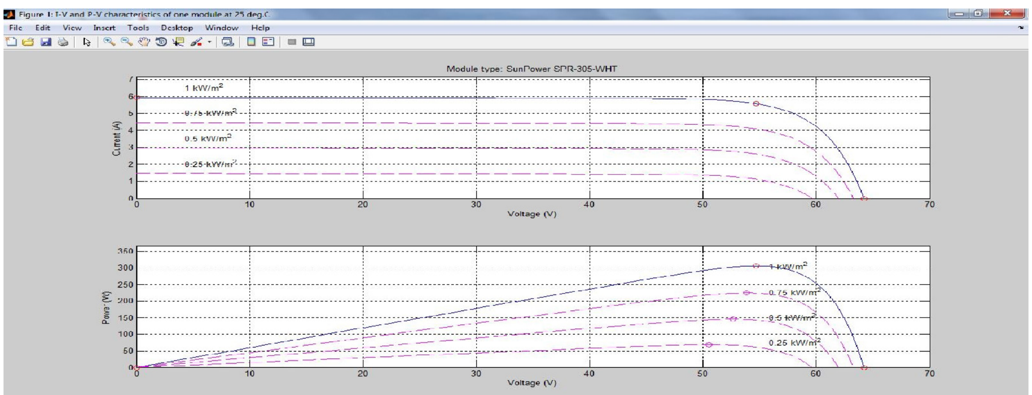

Fig. 7. One module I-V and P-V characteristics

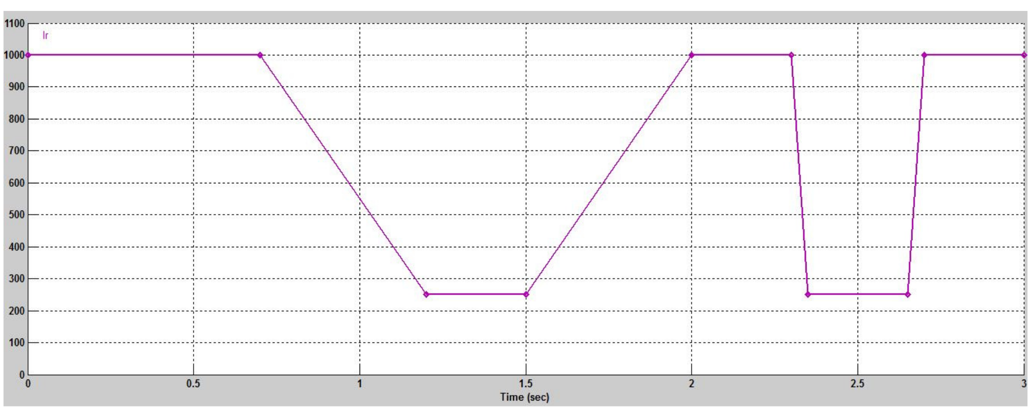

Fig. 8. The radiation as a function of time

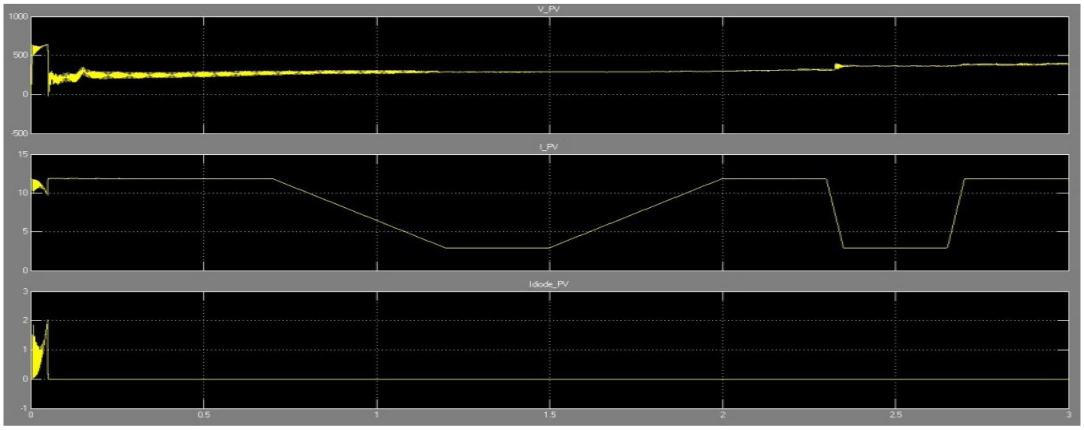

Fig**. 9. The output PV-voltage, PV-current, and the PV diode's current**

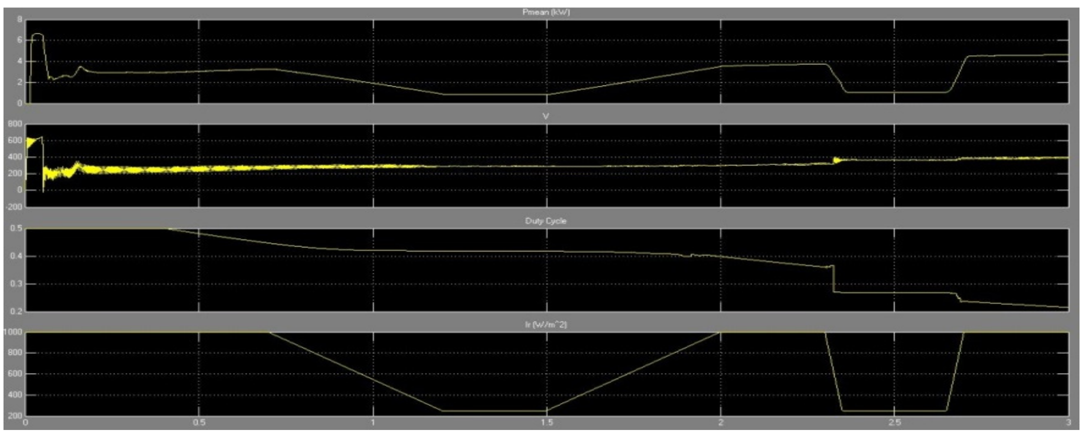

Fig. 10. The Boost converter output mean power, boost converter output voltage, the duty cycle, and the PV array irradiation

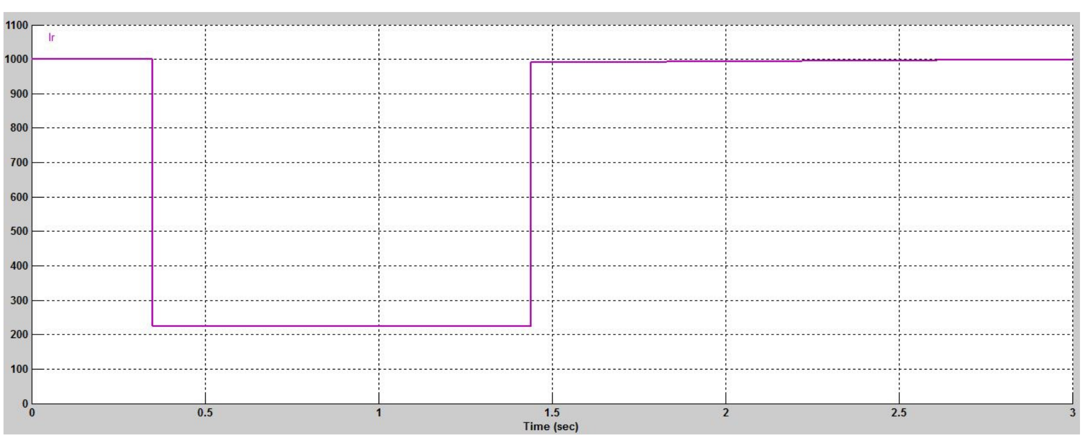

Fig. 11. Step irradiation

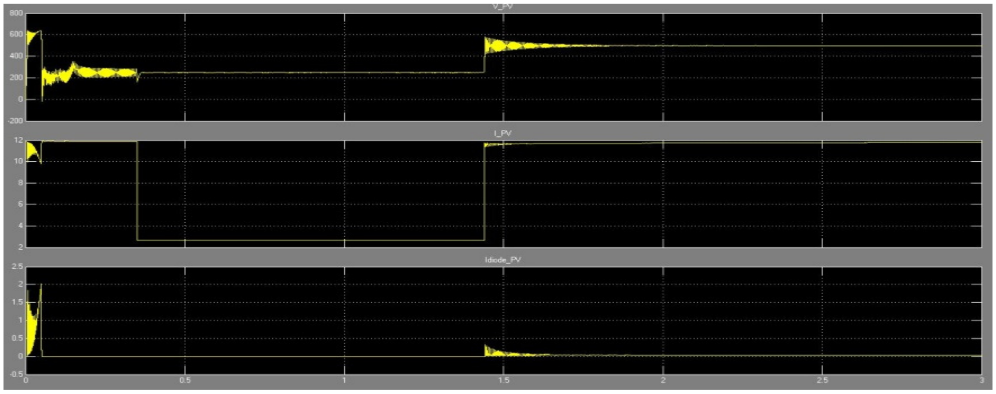

Fig. 12. The boost converter output voltage, output current, and the diode's current

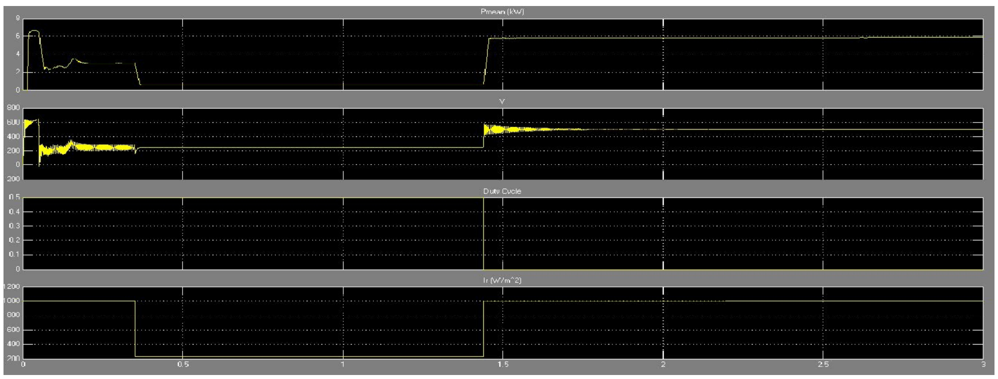

Fig. 13. The boost converter output mean power, output voltage, the duty cycle, and the PV array irradiation

<u>3.1.3 Changing the duty cycle (D) of the boost</u>

The duty cycle set to 0.75 instead of 0.5, and the same parameters of the first case. Fig. 14 shows how the output PV power under such conditions decreases than that of case one.

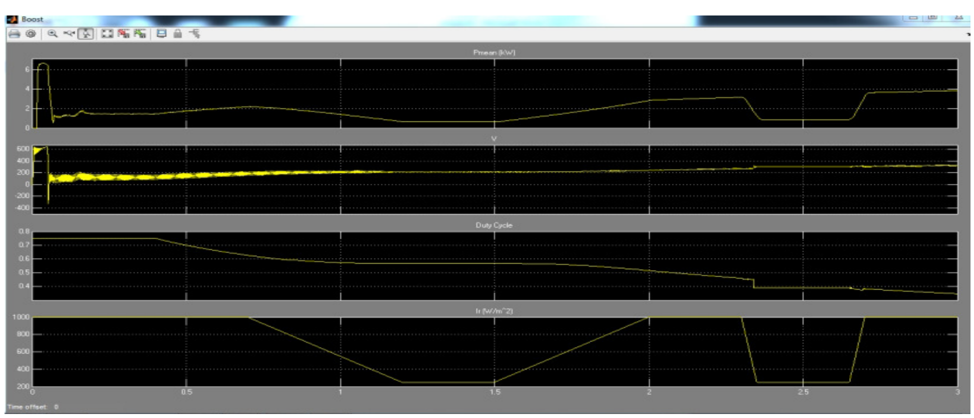

Fig. 14. PV power, boost converter output voltage, duty cycle, and the irradiation

3.1.4 Sand effect on PV array

Sand effect, or any analogue effect like shading, dust, snow, clouds.., e.t.c, can be simulated by adding another signal to the signal of irradiation. As shown in Figs. 15 and 16 shows how the PV current changed following the irradiation variation caused by the sand effect. Leading to a decrease of the output PV power which means minimization of the efficiency and so the performance of the PV.

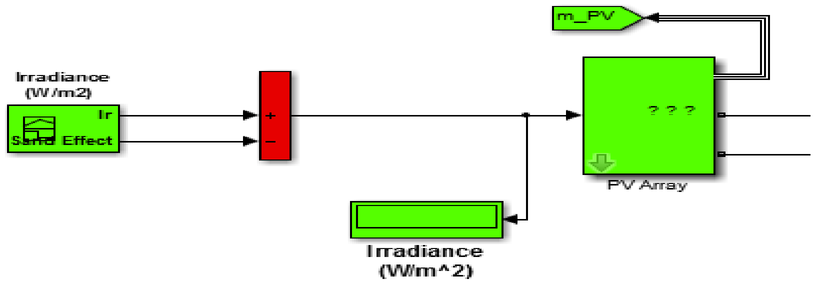

Fig. 15. Sand effect models

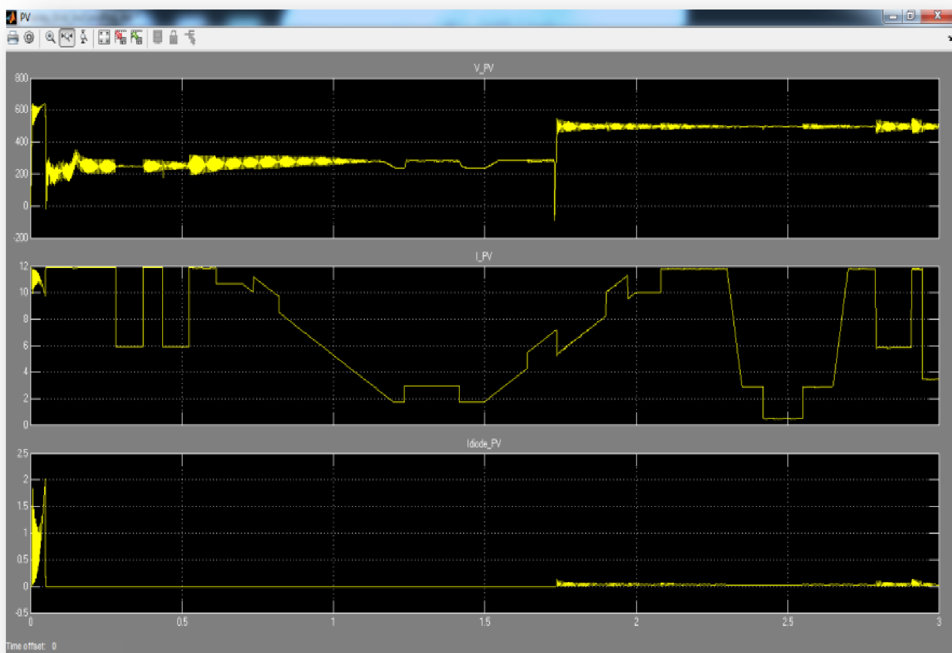

Fig. 16. The PV voltage, PV current, and the diodes current under the sand effect

4. CONCLUSION

The paper presents an approach of modelling a solar PV cell. The model is based on the fundamental circuit equations of a solar PV cell taking the effects of the environmental parameters such as the solar radiation, the cell temperature and the sand effect. The module was simulated on a Matlab/Simulink model using a KYOCERA KD235GX solar panel with 235Wp peak power, such model would provide a tool to predict the I-V, and P-V characteristics of the solar PV cells and to select the proper power electronics and the associated control method to track the maximum power point under the changes of the environmental parameters

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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