MATLAB/Simulink Based Modelling of Solar Photovoltaic Cell

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Abstract-This paper focuses on a Matlab/SIMULINK model of a photovoltaic cell. This model is based on mathematical equations and is described through an equivalent circuit including a photocurrent source, a diode, a series resistor and a shunt resistor. The developed model allows the prediction of PV cell behaviour under different physical and environmental parameters. The model can also be used to extract the physical parameters for a given solar PV cell as a function of temperature and solar radiation. In addition, this study outlines the working principle of PV module as well as PV array. In order to validate the developed model, an experimental test bench was built and the obtained results exhibited a good agreement with the simulation ones.

Keywords-Matlab, SIMULINK, PV, solar cell model, solar array model, solar radiation, maximum power point

1. Introduction

The development of new energy sources is continuously enhanced because of the critical situation of the chemical industrial fuels such as oil, gas and others. Thus, the renewable energy sources have become a more important contributor to the total energy consumed in the world. In fact, the demand for solar energy has increased by 20% to 25% over the past 20 years [1]. The market for PV systems is growing worldwide. In fact, nowadays, solar PV provides around 4800 GW. Between 2004 and 2009, grid connected PV capacity reached 21 GW and was increasing at an annual average rate of 60% [2]. In order to get benefit from the application of PV systems, research activities are being conducted in an attempt to gain further improvement in their cost, efficiency and reliability.

With no pollutant emission, Photovoltaic cells convert sunlight directly to electricity. They are basically made up of a PN junction. Figure 1 shows the photocurrent generation principle of PV cells. In fact, when sunlight hits the cell, the photons are absorbed by the semiconductor atoms, freeing electrons from the negative layer. This free electron finds its path through an external circuit toward the positive layer resulting in an electric current from the positive layer to the negative one.

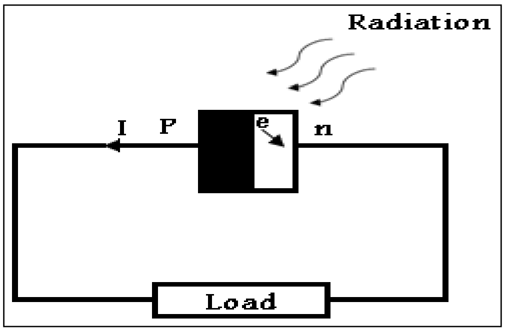

Fig.1. Photocurrent generation principle.

Typically, a PV cell generates a voltage around 0.5 to 0.8 volts depending on the semiconductor and the built-up technology. This voltage is low enough as it cannot be of use. Therefore, to get benefit from this technology, tens of PV cells (involving 36 to 72 cells) are connected in series to form a PV module. These modules can be interconnected in series and/or parallel to form a PV panel. In case these modules are connected in series, their voltages are added with the same current. Nevertheless, when they are connected in parallel, their currents are added while the voltage is the same.

Three major families of PV cells are monocrystalline technology, polycrystalline technology and thin film technologies. The monocrystalline and polycrystalline technologies are based on microelectronic manufacturing technology and their efficiency is in general between 10% and 15% for monocrystalline and between 9% and 12% for polycrystalline. For thin film cells, the efficiency is 10% for a-Si, 12% for CuInSe2 and 9% for CdTe [3]. Thus, the monocrystalline cell that has the highest efficiency is the focus of this paper. This paper carried out a Matlab/SIMULINK model of monocrystalline PV cell that made possible the prediction of the PV cell behaviour under different varying parameters such as solar radiation, ambient temperature, series resistor, shunt resistor, diode saturation current, etc.

The focus of this paper is on solar cell modelling which is discussed in section two. Section three presents the effects of the variation of the solar radiation. In section four, the influence of temperature on the PV cell outputs are investigated. The effects of the series resistance have been presented in section five. Section six focuses on the effects of the shunt resistance. In section seven, the effects of the diode reverse saturation current are studied. The model features and its experimental validation are discussed in sections eight through ten. While conclusions and future works are presented in section eleven.

2. PV cell model

The equivalent circuit of a PV cell is shown in Fig. 2. It includes a current source, a diode, a series resistance and a shunt resistance [4, 5].

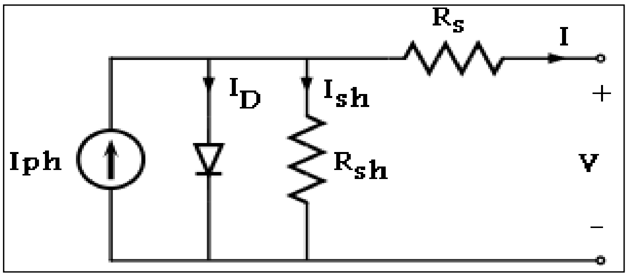

Fig. 2.PV cell equivalent circuit.

In view of that, the current to the load can be given as: [6,7,8]

$$I = I_{ph} - I_s\left(\exp\frac{q(V+R_S I)}{NKT} - 1\right) - \frac{(V+R_S I)}{R_{sh}} \qquad (1)$$

In this equation, I_{ph} is the photocurrent, I_s is the reverse saturation current of the diode, q is the electron charge, V is the voltage across the diode, K is the Boltzmann's constant, T is the junction temperature, N is the ideality factor of the diode, and R_s and R_{sh} are the series and shunt resistors of the cell, respectively.

As a result, the complete physical behaviour of the PV cell is in relation with I_{ph}, I_s, R_s and R_{sh} from one hand and with two environmental parameters as the temperature and the solar radiation from the other hand.

Based on equation (1), the Matlab/SIMULINK model of Fig.3 was developed. For a given radiation, temperature, R_s and R_{sh}, the *I-V* and *P-V* curves are generated as shown in Fig.4.

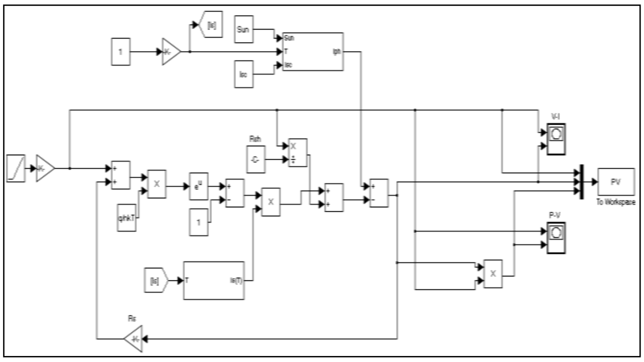

Fig. 3. PV cell Matlab/SIMULINK model.

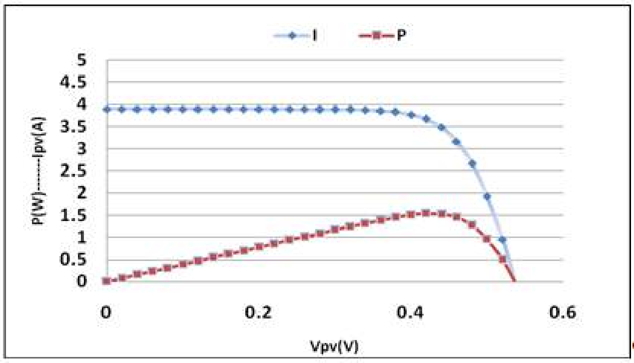

Fig. 4.*I-V* curves and *P-V* curves for a given PV cell

3. Effects of Solar Radiation Variation

The above model includes two subsystems: one that calculates the PV cell photocurrent which depends on the radiation and the temperature according to equation (2) [3].

$$I_{ph} = \left[I_{sc} + K_i(T-298)\right]\frac{\beta}{1000} \qquad (2)$$

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

Based on the above equation, the subsystem of Fig. 5 is obtained and the model simulation results are shown in Figs. 6 and 7.

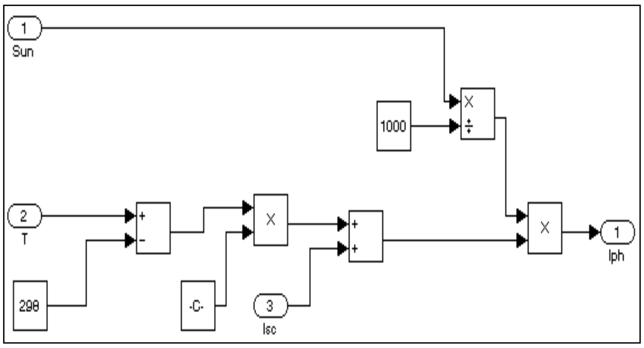

Fig. 5. I_{ph} Matlab/SIMULINK subsystem for varying cell temperature and solar radiation.

As it can be seen from Figs.6 and 7, the PV cell current is strongly dependent on the solar radiation. However, the voltage has a 50 mV increase as the solar radiation increased from 400 W/m^2 to 1000 W/m^2.

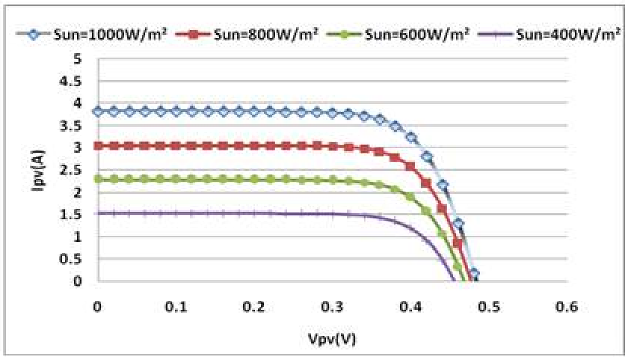

Fig.6.*I-V* curves for different solar radiations.

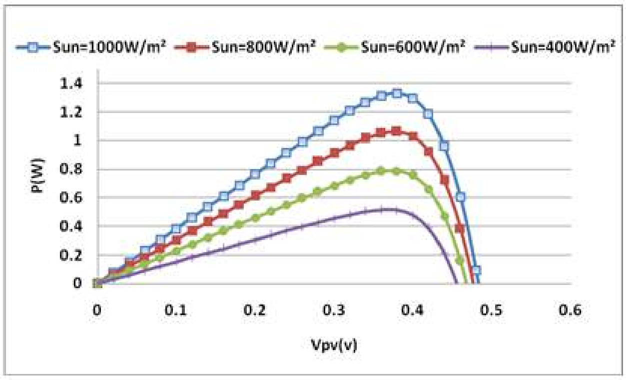

Fig.7.*P-V* curves for different solar radiations.

4. Effect of Varying Cell Temperature

The diode reverse saturation current varies as a cubic function of the temperature and it can be expressed as:

$$I_s(T)=I_s\left(\frac{T}{T_{nom}}\right)^3 \exp\left[\left(\frac{T}{T_{nom}}-1\right)\frac{E_g}{N.V_t}\right] \qquad (3)$$

where I_s is the diode reverse saturation current, T_{nom} is the nominal temperature, E_g is the band gap energy of the semiconductor and V_t is the thermal voltage.

The reverse saturation current subsystem shown in Fig.8 was constructed based on equation (3).

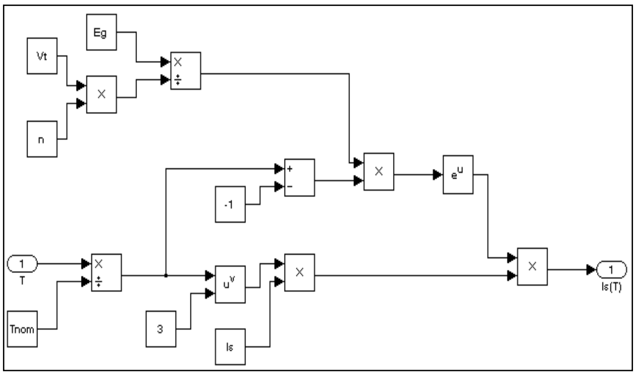

Fig. 8. Matlab/SIMULINK temperature effect subsystem on diode reverse saturation current.

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. This behaviour is validated and presented in Figs. 9 and 10.

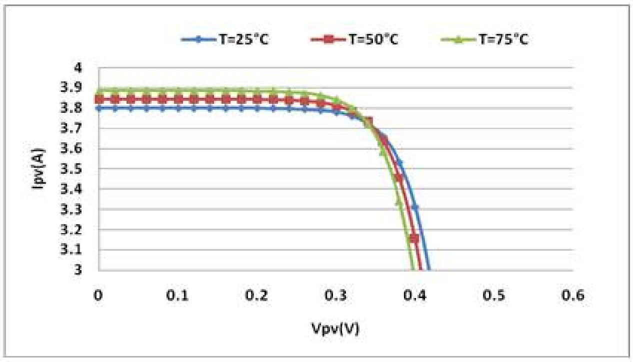

Fig.9.*I-V* curves for different cell temperatures.

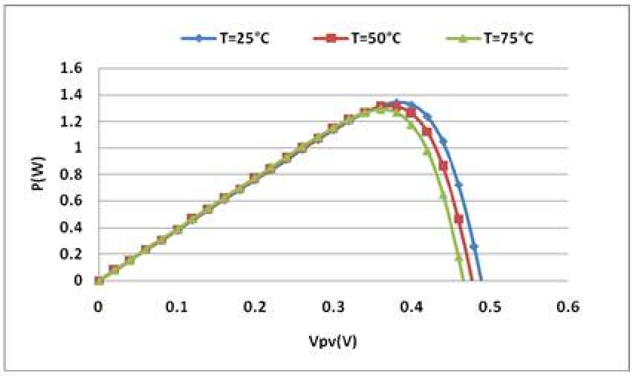

Fig.10.*P-V* curves for different cell temperatures.

5. Effect of Varying R_s

The series resistance of the PV cell is low, and in some cases, it can be neglected [3]. However, to render the model suitable for any given PV cell, it is possible to vary this resistance and predict the influence of its variation on the PV cell outputs. As seen in Figs.11 and 12, the variation of R_s affects the slope angle of the *I-V* curves resulting in a deviation of the maximum power point.

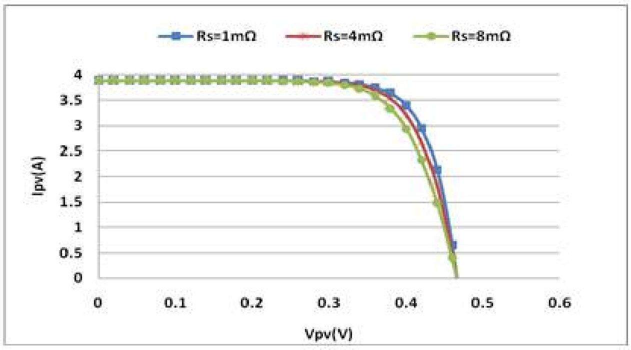

Fig.11.*I-V* curves for different Rs.

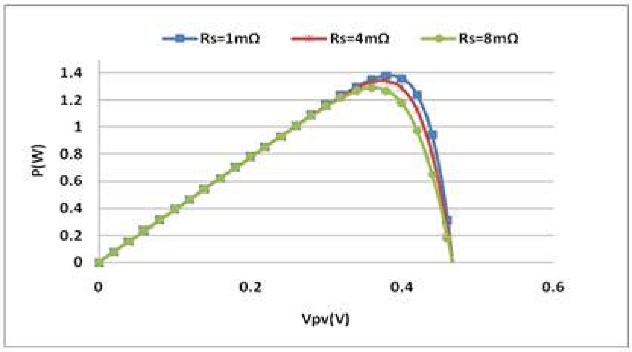

Fig.12.*P-V* curves for different Rs

The simulation was performed for three different values of R_s, namely 1mΩ, 4mΩ and 8mΩ. It was shown that higher values of R_s reduce the power output of the PV cell. According to equation (4), the fill factor, given by equation (4), decreases as R_s increases.

$$FF = \frac{P_{\max}}{V_{oc} I_{sc}} \tag{4}$$

6. Effect of Varying R_{sh}

The shunt resistance of any PV cell should be large enough for higher output power and fill factor. In fact, for a low shunt resistor, the PV cell current collapses more steeply which means higher power loss and lower fill factor. These results can be seen in Figs.13 and 14.

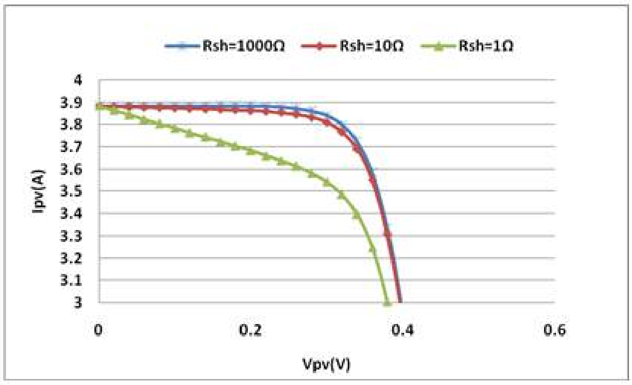

Fig.13.*I-V* characteristics for different Rsh

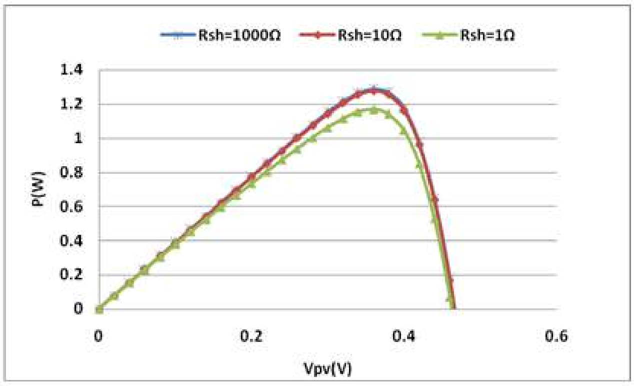

Fig.14.*P-V* curves for different Rsh

7. Effects of Varying I_s.

The model assists in expecting the behaviour of the PV cell for different reverse saturation currents of the diode. The curves of Figs.15 and 16 were plotted for three different values of I_s: 100nA, 10nA and 1nA. The influence of an increase in I_s is evidently seen as decreasing the open-circuit voltage V_{oc}.

8. PV Module

As previously mentioned, a PV module is a connection of tens of PV cells. Figure 17 shows the bloc diagram of Matlab/SIMULINK model of a PV module.

This model contains an external control block permitting an uncomplicated variation of the models' parameters. In this model, 36 PV cell are interconnected in series to form one module. As a result, the module voltage is obtained by multiplying the cell voltage by the cells number while the total module current is the same as the cell's one. The results are shown in Figs.18 and 19.

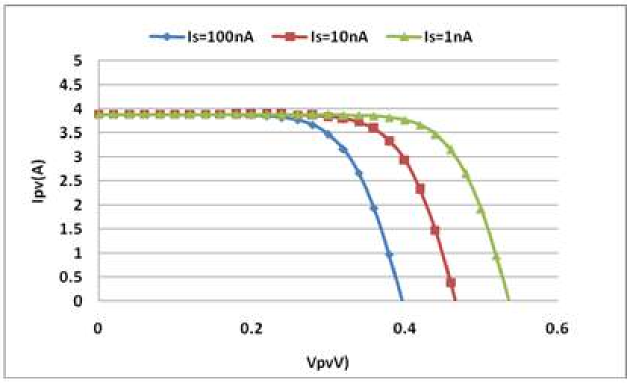

Fig.15.*I-V* curves for different I_s

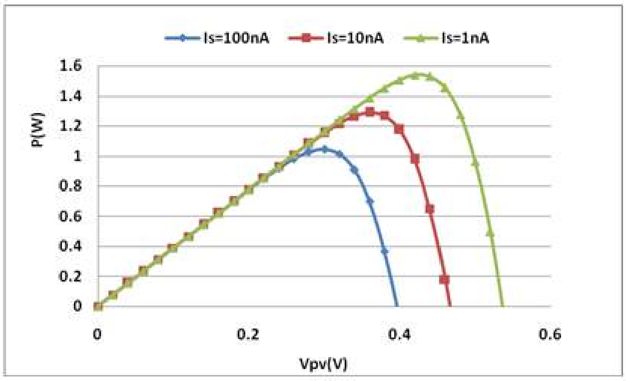

Fig.16.*P-V* curves for different I_s

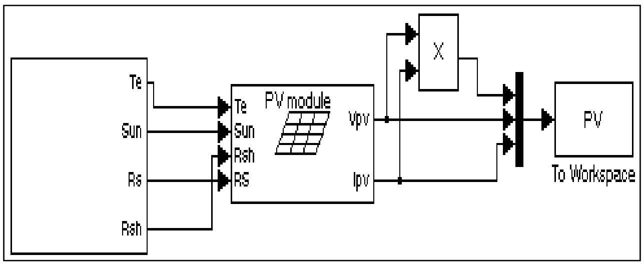

Fig.17. SIMULINK model for the PV module.

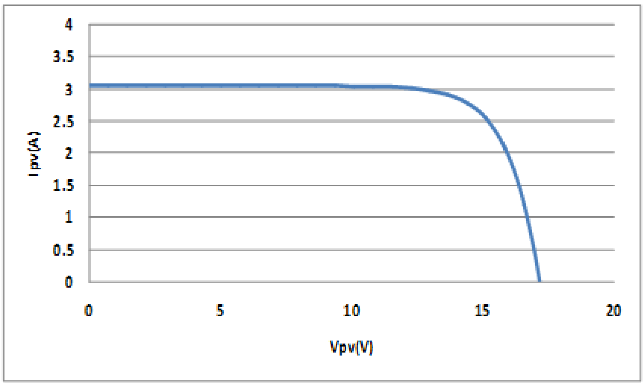

Fig.18. *I-V* curves of the PV module model

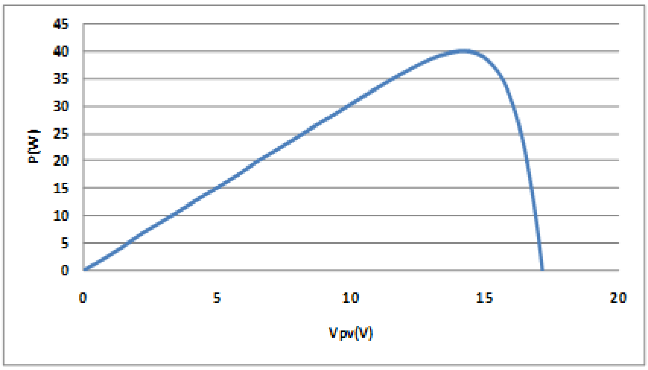

Fig.19. *P-V* curves of the PV module model

9. PV Array

In order to get benefit from these developed models, an array of 6 PV modules has been constructed. In fact, these PV modules were interconnected in series and all of them are connected to the external control block as shown in Fig.20.

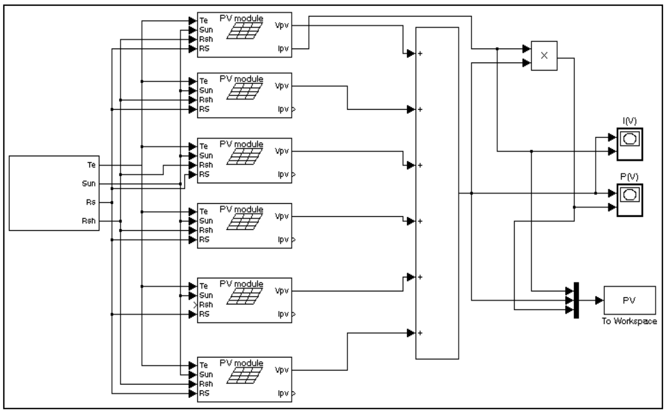

Fig.20. PV array model.

The PV array model was simulated similarly to the model of the PV module and the obtained results are shown in Figs.21 and 22, respectively.

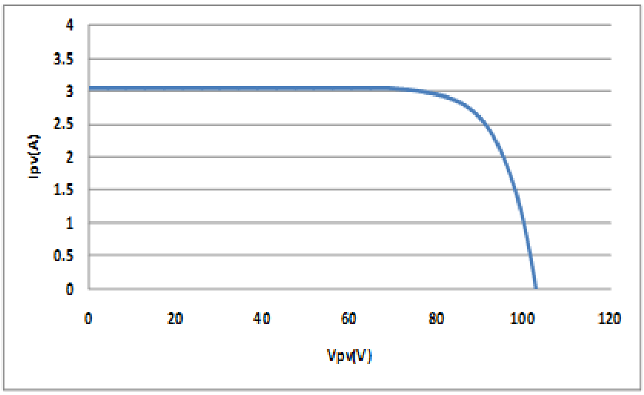

Fig.21. *I-V* curves for the PV array model

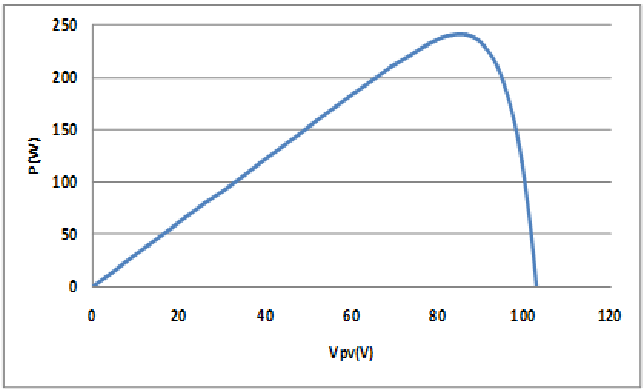

Fig.22. *P-V* curves for the PV array model

10. Experimental Results and Validation

In order to validate the Matlab/SIMULINK model, The PV test bench of Fig.23 was investigated. It consists of a rheostat, a daystar-meter to measure the solar radiation, two digital multi-meters and a solar panel that has the key specifications listed in Table 1.

Fig. 23. Setup of the PVL-124 solar laminate panel.

Table 1. Electrical specifications for the test panel

Solar Laminate PVL-Series Model: PVL-124	
Maximum power	124 W
Voltage at P_{max}	30 V
Current at P_{max}	4.1 A
Open circuit voltage	42 V
Short circuit current	5.1 A

The Matlab/SIMULINK model was evaluated for the PVL-124 solar panel. The results are shown in Fig.24. On the other hand, the experimental results for a solar radiation of 540 W/m^2 are shown in Fig. 25.

The *I-V* and *P-V* simulation and experimental results show a good agreement in terms of short circuit current, open circuit voltage and maximum power.

In this study, the Matlab/SIMULINK model not only helps to predict the behavior of any PV cell under different physical and environmental conditions, also it can be considered a smart tool to extract the internal parameters of any solar PV cell including the ideal factor, series and shunt resistance. Some of these parameters are not always provided by the manufactures.

11. Conclusion

A Matlab/SIMULINK model for the solar PV cell, modules and array was developed and presented in this paper. This model is based on the fundamental circuit equations of a solar PV cell taking into account the effects of physical and environmental parameters such as the solar radiation and cell temperature. The module model was simulated and validated experimentally using the high efficient PVL-124 solar laminate panel.

As a result of the study, one can benefit from this model as a photovoltaic generator in the framework of the Sim-Power-System Matlab/SIMULINK toolbox in the field of solar PV power conversion systems. In addition, such a model would provide a tool to predict the behaviour of any solar PV cell, module and array under climate and physical parameters changes.

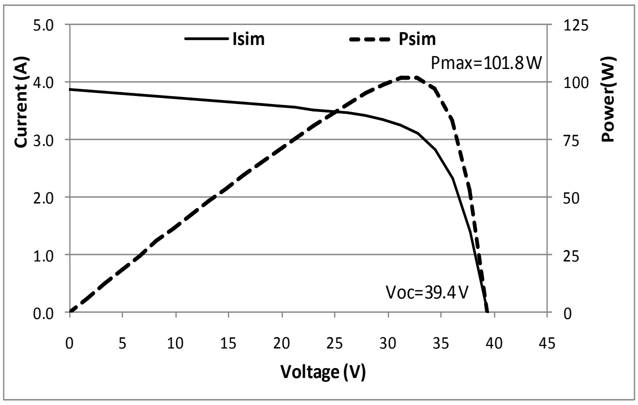

Fig.24.MATLAB simulation results.

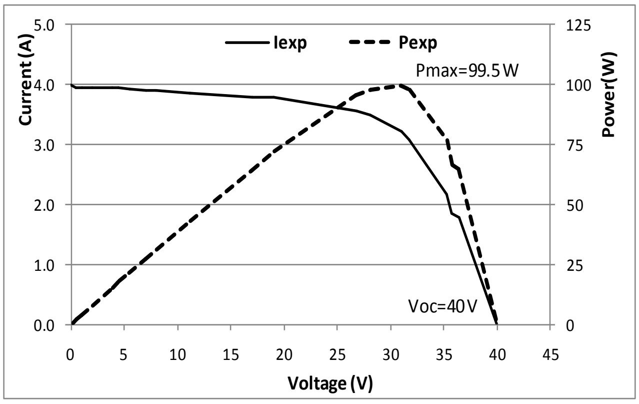

Fig. 25.PVL-124 solar laminate panel experimental results.

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