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Modeling and Simulation of Photovoltaic Module Considering an Ideal Solar Cell

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Abstract: *The main purpose of the present work is to develop a model for an ideal solar cell of a photovoltaic module by using the MATLAB simulation program. The simulation is carried out in order to evaluate the influence of the variation of the temperature of the solar cell, solar irradiance, the diode ideality factor and the energy gap on the I-V and P-V characteristics of the PV cell. This model is based on mathematical equations, including the photocurrent, saturation current, voltage and the output power. The efficiency and the fill factor have been calculated and plotted against various values of the four main considered parameters.*

Keywords: *Photovoltaic conversion, solar cell, efficiency, fill factor.*

1. Introduction

Solar cells are used for the direct conversion of solar energy into electrical energy by means of the photovoltaic effect, that is, the conversion of light into electricity. The device used in photovoltaic conversion is called solar cell. When solar radiation falls on these devices it is converted directly into dc electricity. Solar cells can be grouped to form panels, modules or arrays. The solar cell is a semiconductor diode exposed to light. Solar cells are made of various types of semiconductors using different manufacturing processes [1]. The electrical energy generated by a solar cell depends on the essential properties of the cell and on the incoming solar radiation [2]. Some of the solar radiation photons are absorbed in the p-n junction. Photons with energies lower than the band gap of the solar cell cannot generate voltage or electric current. Photons with energy greater than the band gap generate electricity, but only the energy corresponding to the band gap is used. The remaining energy is wasted as heat inside the solar cell [3]. Improving cell efficiency is one of the major tasks in controlling photovoltaic cells for power generation. This requires a nonlinear current – voltage (I-V) and power-voltage (P-V) characteristics measurements to characterize the performance of the solar cell.

An ideal solar cell is considered in this paper, the series resistance (R_S) and shunt resistance (R_{SH}) have been considered as zero and infinity, respectively. The equivalent circuit of a solar cell has been used in the paper. The four parameters implemented in the equivalent circuit are temperature (T), irradiance (G), diode ideality factor (n), and energy gap (E_g).

2. PV CELL MODEL

A solar cell is a unit of a photovoltaic module consisting of a P-N junction made in a thin layer of a semiconductor. The P-N junction converts the solar electromagnetic radiation to electricity [4, 5, 6]. When light strikes the solar cell the electrons will jump from the valence band to the conduction band in the semiconductor. The most common model used to predict energy production in a photovoltaic cell is the single diode lumped circuit model [7, 8], as shown in figure (1).

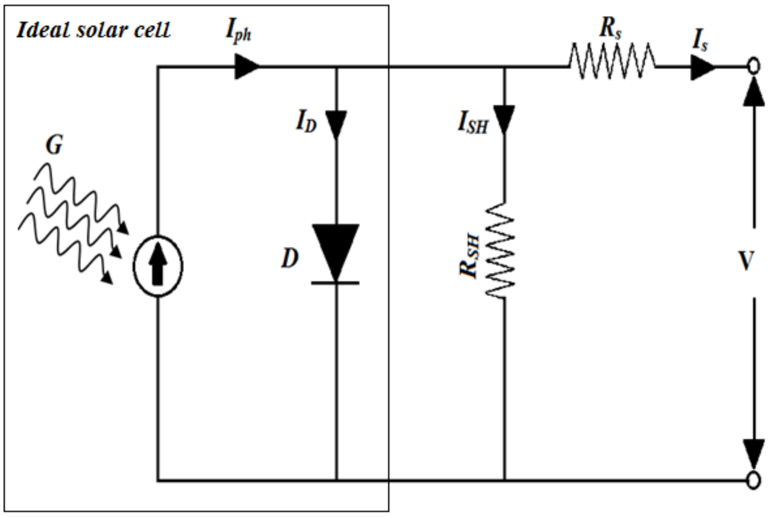

Figure 1. *Electrical circuit of the single diode model*

In Figure 1, G is the solar irradiance, I_{ph} is the photo generated current, I_D is the diode current, I_s is the output current, and V is the terminal voltage.

The I-V characteristics of the ideal solar cell with a single diode are given by:

$$I_s = I_{ph} - I_o\left(e^{qv/nkT} - 1\right) \tag{1}$$

Where I_o is the diode reverse bias saturation current, q is the electron charge, n is the diode ideality factor, k is the Boltzmann's constant, and T is the cell temperature.

The short circuit current I_{sc} is the highest value of the current produced by the cell. The short circuit current I_{sc} is given by:

$$I_{sc} = I_s = I_{ph} \quad \text{for} \quad V = 0 \tag{2}$$

The Photo generated I_{ph} is given by:

$$I_{ph} = \left(I_{ph}\left(T_{ref}\right) + k_i\left(T - T_{ref}\right)\right) \times \frac{G}{G_{nom}} \tag{3}$$

The open circuit voltage V_{oc} is the highest value of the voltage of the cell [9] . The open circuit voltage V_{oc} is given by:

$$V_{oc} = \frac{nkT}{q} \ln\left(1 + \frac{I_{sc}}{I_o}\right) \quad \text{for } I = 0 \tag{4}$$

The output power is given by:

$$P = V\left[I_{sc} - I_o\left(e^{qv/nkT} - 1\right)\right] \tag{5}$$

The diode saturation current at the operating temperature of the cell is given by:

$$I_{ot} = I_o\left(\frac{T_c}{T_{ref}}\right)^3 e^{\frac{qE_g}{nk}\left(\frac{1}{Tref} - \frac{1}{Tc}\right)} \tag{6}$$

Where Io is the diode saturation current at the reference condition, T_c is the p-n junction cell temperature, T_{ref} is the cell p-n junction temperature at the reference condition, and E_g is the band gap.

The efficiency of the solar cell was calculated by applying the following relation:

$$\eta = \left(\frac{V_m I_m}{GA}\right) \times 100\% \tag{7}$$

Where:

V_m – maximum voltage [V], I_m – maximum current [A], G – intensity of radiation [W/m^2], A – area of the cell [m^2].

The fill factor of the current – voltage characteristics of solar cells can be calculated by using the following relation:

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{8}$$

Where:

V_{oc}– open circuit voltage [V], I_{sc} – short circuit current [A].

Figure (2) shows number of cells in PV module connected on series (N_s) and Parallel (N_p). The equations were rewritten as following:

$$\begin{cases} I_s = I_s \times N_p \\ V_{pv} = V_{pv} \times N_s \\ I_{ph} = I_{ph} \times N_p \\ V_{oc} = V_{oc} \times N_s \end{cases} \tag{9}$$

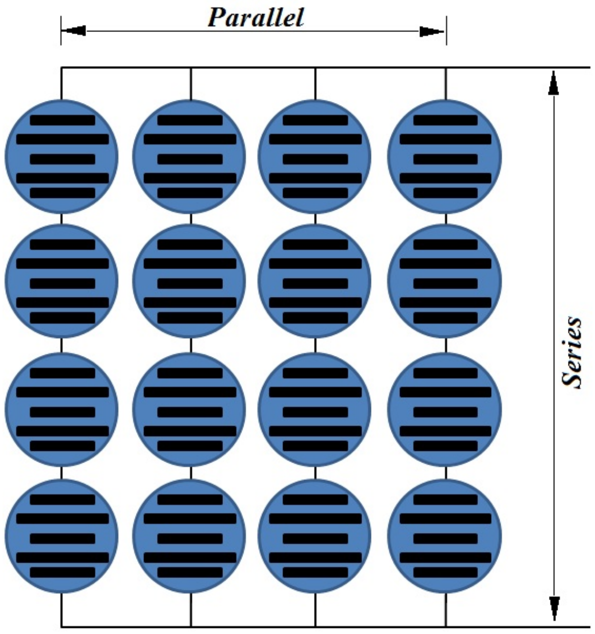

Figure 2. *PV module*

3. Results and Discussion

Four general programs are designed in MATLAB and based on the mathematical equations, which are representing the photovoltaic module model. These programs have been developed to calculate the current from voltage data, considering the ideal solar cell (R_S= 0 and $R_{SH} = \infty$). The simulation programs were carried out at varying temperature (T – ^{o}C), solar irradiance (G –

Watt/m^2), ideality diode factor (n) and energy gap ($E_g - eV$). Figures 3 and 4 show the I-V and P-V characteristics of an ideal solar cell module at various temperatures between 10 and 50o C. It is clear that the short circuit current is inversely proportional to the temperature. The results show that the output power of the PV cell module changes with the temperature and that the variation in the short-circuit current is much less than the variation in the open-circuit voltage [10].

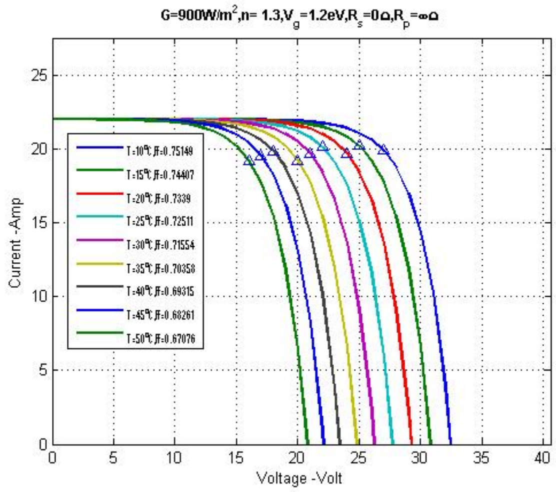

Figure 3. *I-V characteristics for a solar cell module at various temperatures.*

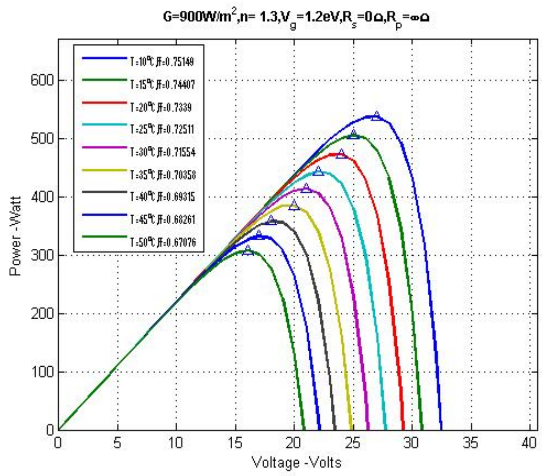

Figure 4. *P-V characteristics of a solar cell module at various temperatures.*

Figures 5 and 6 show the dependence of the fill factor and the efficiency on the temperature, respectively. The figures show that the values of the fill factor and the efficiency fall with increasing temperature.

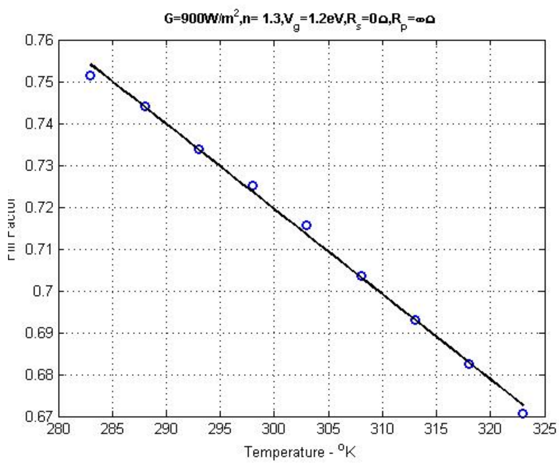

Figure 5. *Fill factor of a PV module as a function of the temperature.*

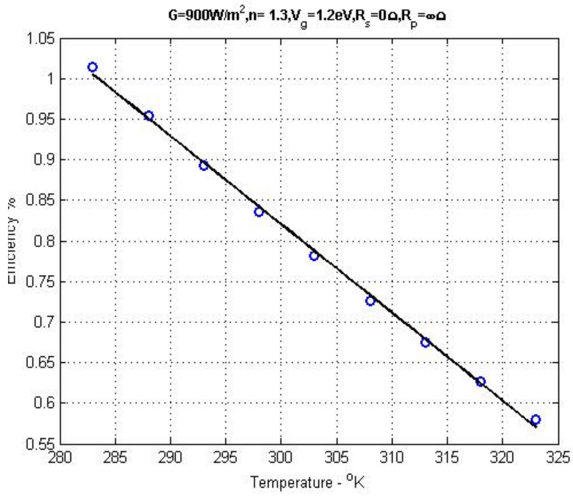

Figure 6. *Efficiency of a PV module as a function of the temperature.*

Figures 7 and 8 show the I-V and P-V characteristics of a PV module at various solar irradiances between 400 and 1000 W/m^2. Figures 9 and 10 show the dependence of the fill factor and the efficiency on the solar irradiance, respectively. It is obvious that there is an increase in the values of the fill factor and the efficiency with increasing solar irradiance and this is due to the fact that the open-circuit voltage is logarithmically dependent on the solar irradiance. However, the short-circuit current is directly proportional to the radiation intensity [10].

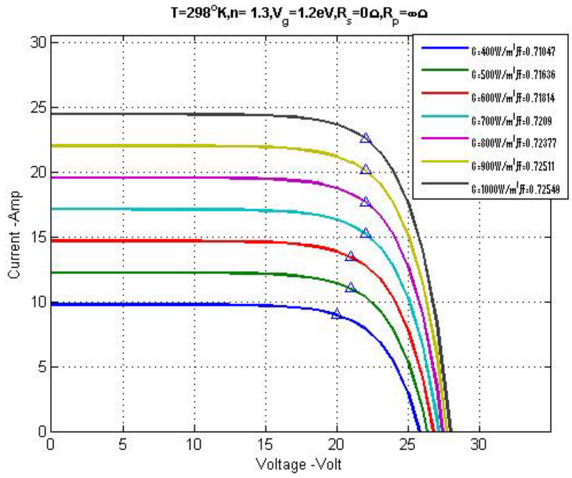

Figure 7. *I-V characteristics of a PV module at various solar irradiance.*

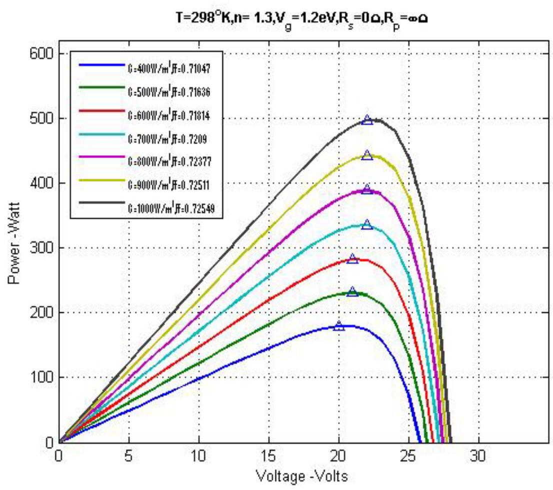

Figure 8 *P-V characteristics of a PV module at various solar irradiance.*

The I-V and P-V characteristics of the PV module at various diode ideality factors varied between 1 and 2 and are shown in figures 11 and 12, respectively. There is an obvious increase in the open circuit voltage with increasing ideality factor values. The forward bias gate voltage depends on the ideality factor which increases with increasing doping concentration [11]. Figures 13 and 14 show the dependence of the fill factor and the efficiency on the ideality factor, respectively. The two figures show the obvious increase of fill factor and the efficiency with increasing the values of the diode ideality factor.

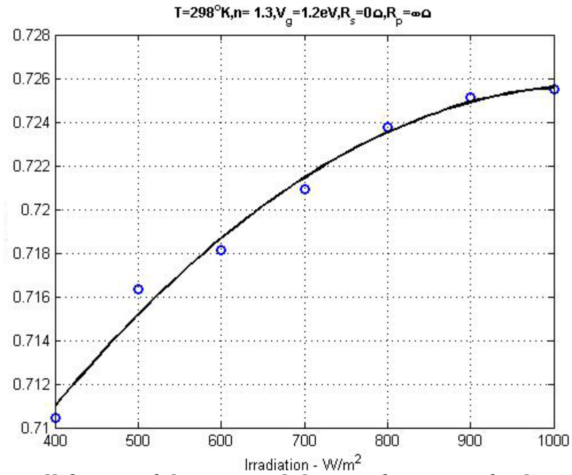

Figure 9. *Fill factor of the PV module as a function of solar Irradiance*

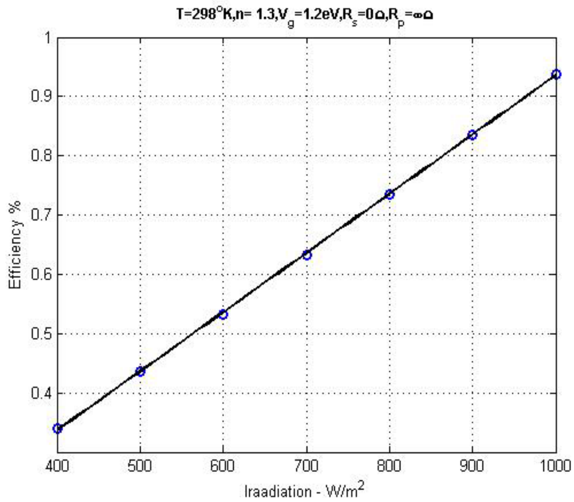

Figure 10. *Efficiency of the PV module as a function of solar Irradiance*

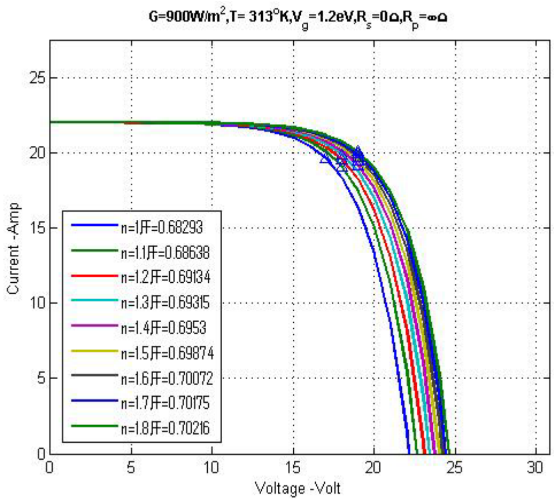

Figure 11. *I-V characteristics of PV module at various diode ideality factors*

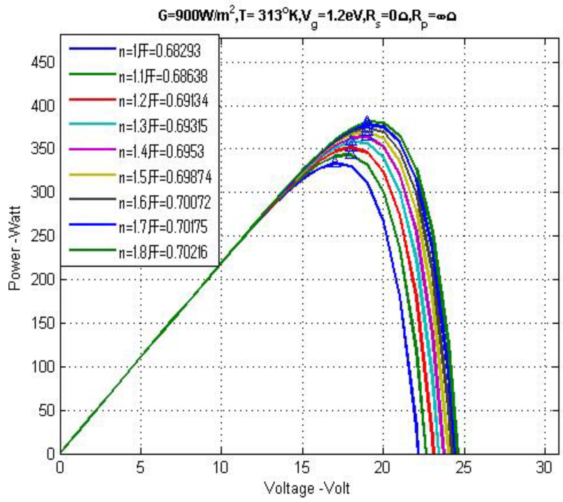

Figure 12. *P-V characteristics of PV module at various diode ideality factors*

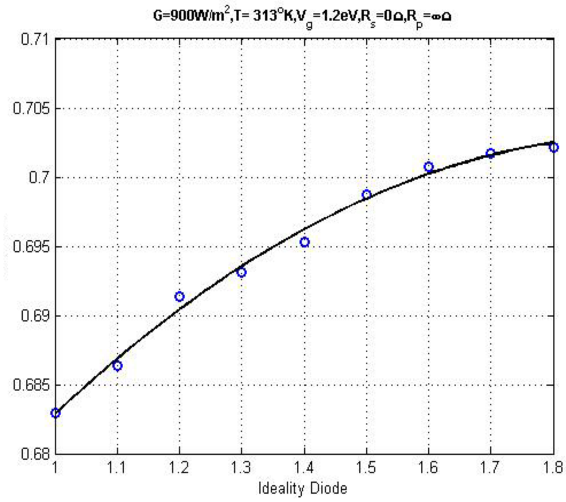

Figure 13. *Fill factor of PV module as a function of diode ideality factor*

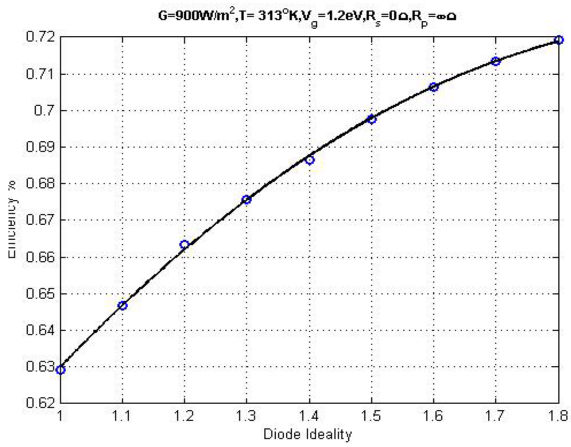

Figure 14. *Efficiency of PV module as a function of diode ideality factor*

The I-V and P-V characteristics of the PV module at various energy gaps ranged between 0.4 and 1.6 eV and are shown in figures 15 and 16, respectively. It is clear that there is an obvious reduction in the open circuit voltage with increasing values of the energy gap because when the band gap is large most of the photons cannot be absorbed. In contrast when the band gap is small most of the photons have much more energy than necessary to excite electrons across the band gap [12, 13]. Figures 17 and 18 show the relation between the fill factor and the efficiency on the energy gap.

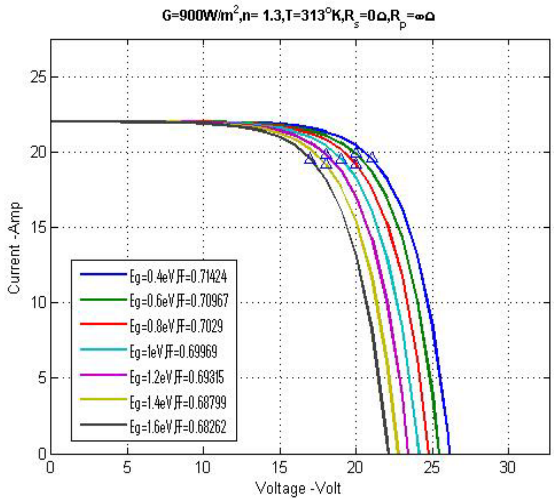

Figure 15. *I-V characteristics of PV module at various energy gaps*

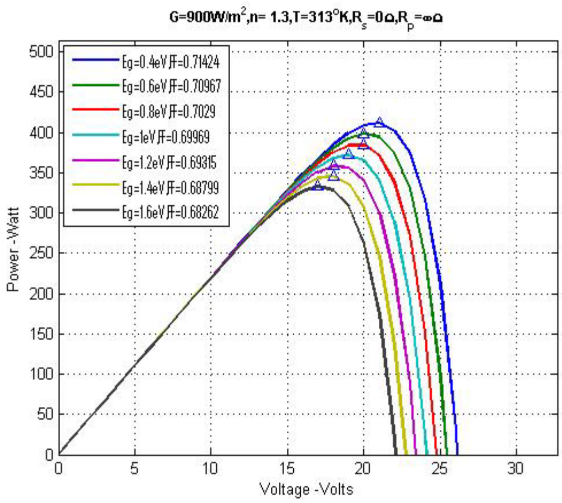

Figure 16. *P-V characteristics of PV module at various energy gaps*

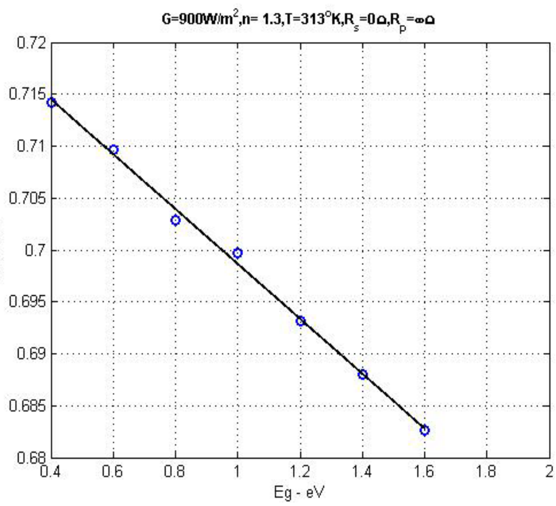

Figure 17. *Fill factor of PV module as a function of energy gap*

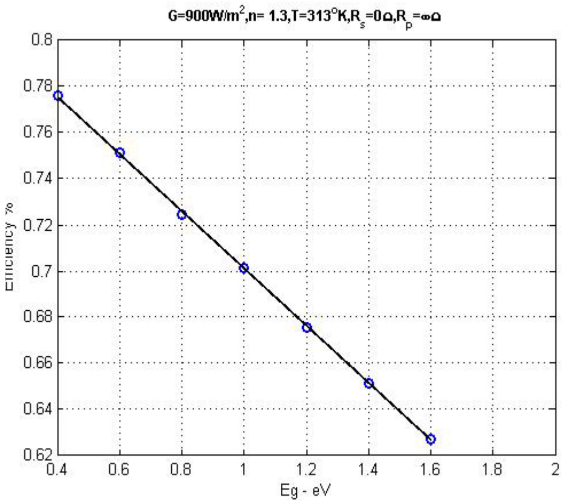

Figure 18. *Efficiency of PV module as a function of energy gap*

4. CONCLUSION

The PV module behavior was studied in this work using the ideal solar cell model. Simulations were carried out by MATLAB. Involved effects are temperature dependence, solar intensity change, diode ideality factor and energy gap influence. The amount of maximum power, the efficiency and the fill factor have appeared a remarkable variation by changing the considered parameters. There was an inverse relationship between the fill factor and the efficiency of a PV module with the temperature and the energy gap. In contrast they showed a clear increasing with the solar irradiance and the ideality factor respectively.

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