

## MODELING AND SIMULATION OF A PHOTOVOLTAIC CELL CONSIDERING SINGLE-DIODE MODEL

MESSAOUDA AZZOUZI<sup>1</sup> & MILAN STORK<sup>2</sup>

<sup>1</sup>Faculty of Science and Technology, Ziane Achour University of Djelfa, Cité Ain Chih, Djelfa, Algeria

<sup>2</sup>Applied Electronics and Telecommunications, University of West Bohemia, Pilsen, Czech Republic

### ABSTRACT

Solar energy is one of the most important types of renewable energies. Many models of solar cell had been proposed since the beginning of the solar energy exploitation. The present paper focuses on single-diode photovoltaic cell models. The I-V and P-V characteristics are presented for each model in function of the series resistance, the shunt resistance, the temperature and the irradiation. More than that, a comparison between an ideal model single-diode solar cell, a model of single-diode solar cell with a series resistance and a model of single-diode solar cell with series and shunt resistances is also presented. Different results were visualized and commented and a conclusion had been drawn.

**KEYWORDS:** PV Cell, Solar Energy, Single Diode, Modeling, I-V/P-V Characteristics, 1M3P, 1M4P, 1M5P

### Acronyms

PV: Photovoltaic

I-V: current-voltage

P-V: power-voltage

1M3P: single mechanism, three parameters

1M4P: single mechanism, four parameters

1M5P: single mechanism, five parameters

$I_{ph}[A]$ : the current generated by the incident light

$I_s [A]$ : the diode reverse bias saturation current

$I_{sh} [A]$ : the shunt resistance current

$I_{sc}[A]$ : short circuit current

$I_{pv}[A]$ : the output current

$V_{pv}[V]$ : the terminal voltage

$V_{ph}[V]$ : the photovoltaic voltage

$I_d[A]$ : the diode current

$V_{oc} [V]$ : open circuit voltage

$q$ : the electron charge [ $1.60217646 \cdot 10^{-19} \text{C}$ ]

$k$ : the Boltzmann constant [ $1.3806503 \cdot 10^{-23} \text{J/K}$ ]

$T$  [K]: the temperature of the PN junction

$E$  [ $\text{W/m}^2$ ] is the irradiation

$R_s$  [ $\Omega$ ]: series resistance

$R_{sh}$  [ $\Omega$ ]: shunt resistance

$m$ : the ideality factor of the diode

## INTRODUCTION

In recent years, significant photovoltaic deployment has occurred, particularly in many developed countries. Also, PV energy is going to become an important source in coming years it has highest source of sunshine radiation. This last is composed of photons of different energies, and some are absorbed at the PN junction. Photons with energies lower than the band gap of the solar cell are useless and generate no voltage or electric current. Photons with energy superior to the band gap generate electricity, but only the energy corresponding to the band gap is used [1].

Solar cells are basically made of semiconductors which are manufactured using different process. These semiconductors convert the energy of sunlight directly into electricity by the photovoltaic effect. Many mathematical models have been developed to represent the highly nonlinear behavior resulting from semiconductor junctions in order to assess the performance of the PV cell. In our case, we consider single diode model [2].

## MODELING OF SINGLE DIODE SOLAR CELL

Equivalent circuit models define the entire I-V curve of a cell, module, or array as a continuous function for a given set of operating conditions. Three equivalent circuit models can be used to describe a single diode model such as: the ideal solar cell or the 1M4P model, solar cell with series resistance called also 1M5P, and solar cell with series and shunt resistances which is called 1M5P [11].

### Ideal Solar Cell (1M4P)

The I-V characteristics of a solar cell have an exponential characteristic similar to that of a diode [3]. The ideal equivalent circuit of solar cell is a current source in parallel with a single-diode. This model involves the following four unknown parameters:  $m$ ,  $I_{ph}$ , and  $I_s$ , this model is also called 1M3P (Single Mechanism, Three Parameters). The configuration of the simulated ideal solar cell with single-diode is shown in Figure 1.

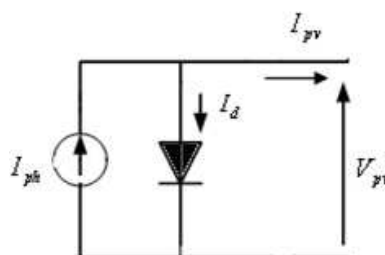


Figure 1: Equivalent Model of Single Diode Ideal Solar Cell (1M3P)

The characteristic equation is deduced directly from the Kirchhoff law:

$$I_{pv} = I_{ph} - I_d \quad (1)$$

The diode current is  $I_d = I_s \left( e^{\frac{qV_{pv}}{mkT}} - 1 \right)$  so the output current is presented by the following non linear I-V equation:

$$I_{pv} = I_{ph} - I_s \left( e^{\frac{qV_{pv}}{mkT}} - 1 \right) \quad (2)$$

For the same irradiation and PN junction temperature conditions, the short circuit current  $I_{sc}$  is the greatest value of the current generated by the cell and the open circuit voltage  $V_{oc}$  is the greatest value of the voltage at the cell terminals [3]. They are given by:

$$I_{sc} = I_{pv} = I_{ph} \quad (3)$$

for  $V_{pv}=0$

$$V_{pv} = V_{oc} = \frac{mkT}{q} \ln \left( 1 + \frac{I_{ph}}{I_s} \right) \quad (4)$$

for  $I_{pv}=0$

The output power is:

$$P = V_{pv} \left[ I_{sc} - I_s \left( e^{\frac{qV_{pv}}{mkT}} - 1 \right) \right] \quad (5)$$

### Solar Cell with Series Resistance

More accuracy can be introduced to the model by adding a series resistance. The electric scheme equivalent to this model is shown in Figure 2. This model involves the following four unknown parameters:  $m$ ,  $I_{ph}$ ,  $R_s$  and  $I_s$  model which is also called 1M4P (Single Mechanism, Four Parameters) [4].

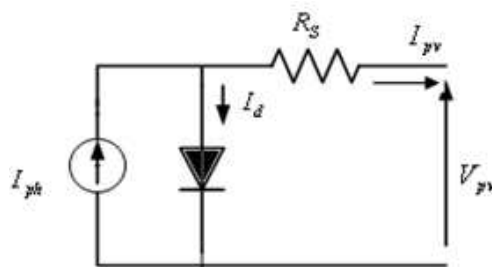


Figure 2: Equivalent Model of Single Diode Solar Cell with Series Resistance (1M4P)

The diode current is:

$$I_d = I_s \left( e^{\frac{q(V_{pv} + R_s I_{pv})}{mkT}} - 1 \right)$$

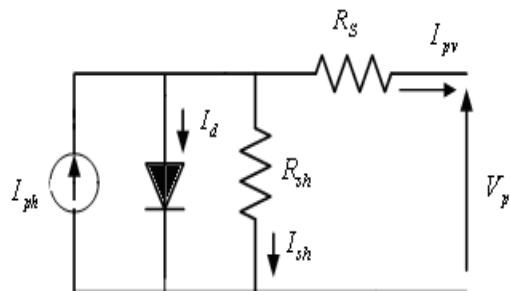
So the I-V characteristics of the solar cell with single-diode and series resistance are given by:

$$I_{pv} = I_{ph} - I_s \left( e^{\frac{q(V_{pv} + R_s I_{pv})}{m k T}} - 1 \right) \quad (6)$$

For the same irradiation and PN junction temperature conditions, the inclusion of a series resistance in the model implies the use of a recurrent equation to determine the output current in function of the terminal voltage. A simple iterative technique initially tried only converged for positive currents [5].

### Solar Cell with Series and Shunt Resistances (1M5P)

The photovoltaic cell in this case is represented by the circuit of Figure 3 which consists of a current source modeling the light flux, the losses are modeled by two resistances: shunt resistance, and series resistance. The model thus involves the following five unknown parameters:  $m$ ,  $I_{ph}$ ,  $R_s$ ,  $R_{sh}$  and  $I_s$ . This model is also called 1M5P (Single Mechanism, Five parameters) [4].



**Figure 3: Equivalent Model of Single Diode Solar Cell with Series and Shunt Resistances (1M5P)**

The characteristic equation can be deduced directly by using the Kirchhoff law:

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (7)$$

Where the diode current is:

$$I_d = I_s \left( e^{\frac{q(V_{pv} + R_s I_{pv})}{m k T}} - 1 \right)$$

and the shunt current is:

$$I_{sh} = \frac{V + R_s I_{pv}}{R_{sh}}$$

The relationship between the PV cell output current and terminal voltage according to the single-diode model is governed by equation:

$$I_{pv} = I_{ph} - I_s \left( e^{\frac{q(V_{pv} + R_s I_{pv})}{m k T}} - 1 \right) - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (8)$$

For the same irradiation and PN junction temperature conditions, the inclusion of a series resistance in the model implies the use of a recurrent equation to determine the output current in function of the terminal voltage. A simple iterative technique initially tried only converged for positive currents [6]. The short circuit current  $I_{sc}$  and the open circuit voltage  $V_{oc}$  are given by:

The modeling of the PV cell in the three cases was done applying the previous equations. Many types of simulation are carried out depending on the chosen model and the selected parameters.

## INFLUENCES OF ENVIRONMENTAL AND PHYSICAL PARAMETERS

### Influence of Irradiation and Temperature

In the three models the temperature is maintained constant at  $25^{\circ}\text{C}$  and by varying the irradiation ( $250\text{W}/\text{m}^2$ ,  $500\text{W}/\text{m}^2$ ,  $750\text{W}/\text{m}^2$ ,  $1000\text{W}/\text{m}^2$ ). Figure 4 shows the Matlab program results under these conditions on I-V and P-V characteristics respectively. It is clear that current generated by the incident light depends on irradiation, the higher the irradiation, the greater the current. On the other hand, voltage is staying almost constant and it is not going to. The influence of irradiation on maximum power point is clear, the higher the irradiation, the major of the maximum power point will be [6].

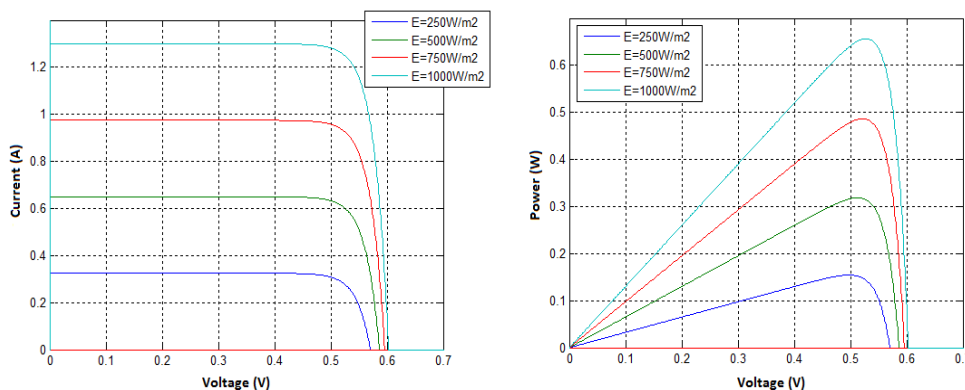


Figure 4: Influence of the Irradiation

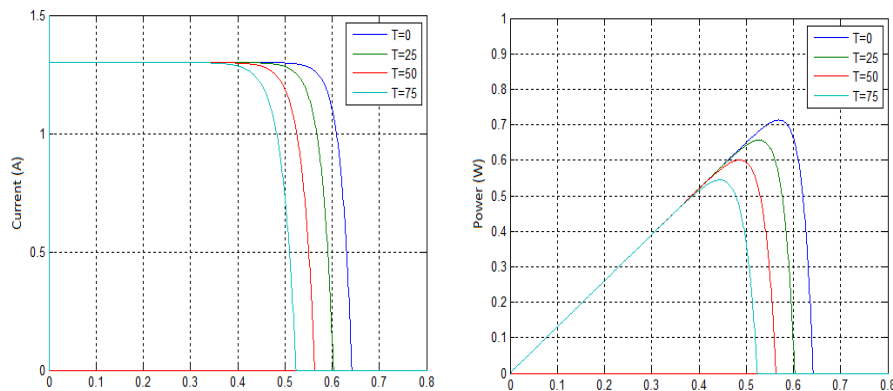
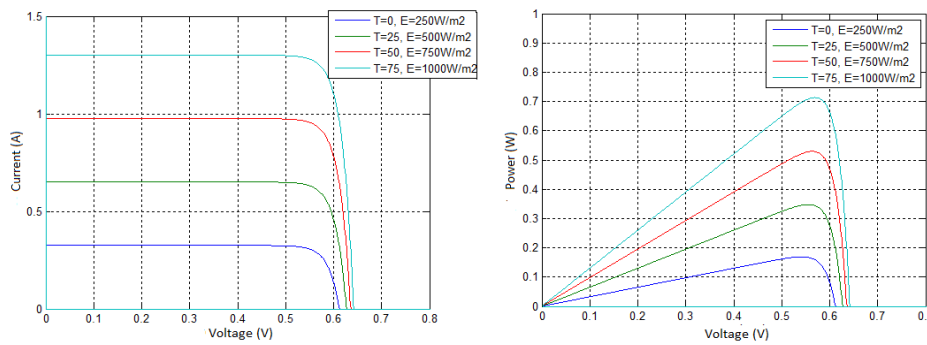
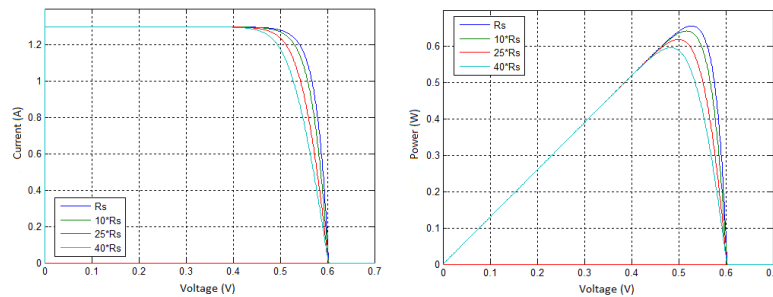


Figure 5: Influence of the Temperature

Second the irradiation is maintained constant at  $1000\text{W}/\text{m}^2$  and varying temperature ( $25^{\circ}\text{C}$ ,  $50^{\circ}\text{C}$ ,  $75^{\circ}\text{C}$ ,  $100^{\circ}\text{C}$ ) will generate the characteristic curves. Figure 5 show the simulation results of I-V and P-V characteristics respectively under the same conditions. The current generated by the incident light is going to stay constant although it increases slightly while the voltage decreases. The effect of the temperature increase decreases voltage and power. Figure 6 shows the influence of both the irradiation and the temperature, we can remark that the I-V and P-V curves are similar to these of the irradiation influence with slightly higher values of power; the effect of the temperature in this case is almost ignored [5].



**Figure 6: Influence of Temperature and Irradiation**



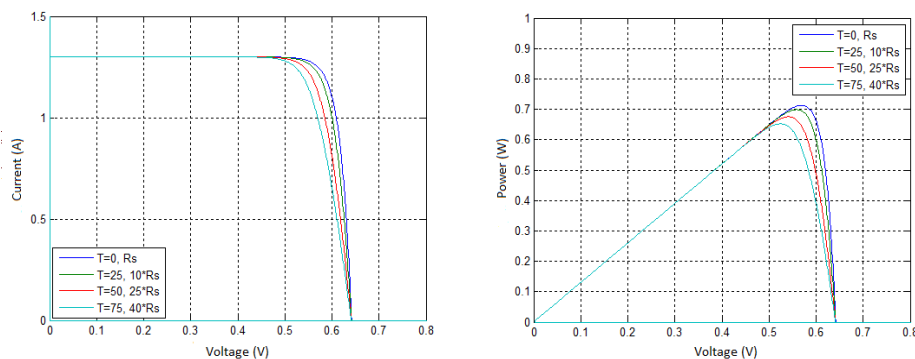
**Figure 7: Influence of Series Resistance**

### Influence of Series Resistance and Temperature

Figure 7 shows the influence of the serial resistance on the characteristic I-V and P-V of 1M4P and 1M5P photovoltaic cells. The series resistance is the slope of the characteristic in the area where the PV cell behaves as a voltage generator it does not change the open circuit voltage, and when it is high, it decreases the value of the short circuit current. The increase of the series resistance results in a decrease in the slope of the power curve. The influence of both the series resistance and the temperature on the same previous models is presented in Figure 8, where the short circuit current took the same value while the open circuit voltage is increased [5].

### Influence of Series Resistance and Irradiation

The following figures show the importance of the series resistance, which indicates the difference between the different models. In Figure 10, the performance of a 1M4P PV cell is much degraded when Rs and the irradiation are high, on the other side the model 1M5P is not so influenced by the series resistance as the 1M4P model [7].



**Figure 8: Influence of Series Resistance and Temperature**

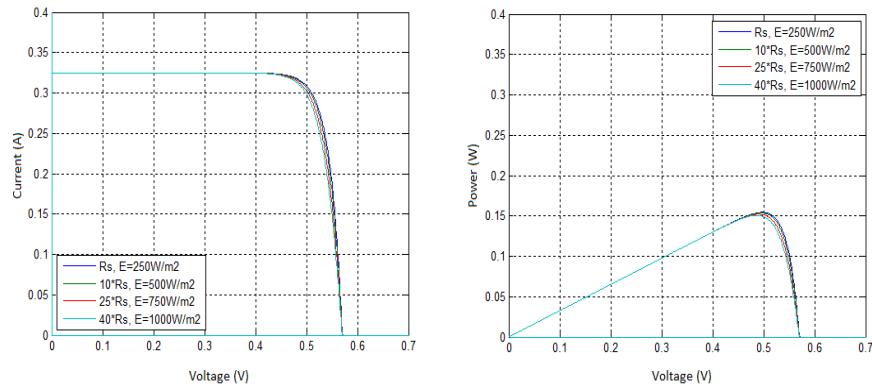


Figure 9: Influence of Series Resistance and Irradiation for 1M4P Model

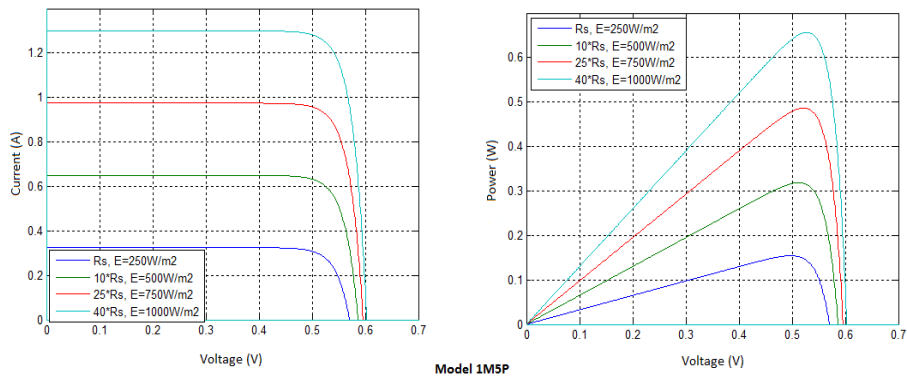


Figure 10: Influence of Series Resistance and Irradiation for 1M5P Model

**Influence of Shunt Resistance and Temperature**

The shunt resistance is a resistance which takes into account the unavoidable leakage of current that occurs between the terminals of a solar cell. In general, when the shunt resistance is very high, its effect is felt especially in the generation of power. The influence of the shunt resistance on the current-voltage characteristics results in a slight decrease in open circuit voltage and an increase of the slope of the I-V curve of the cell in the area corresponding to operation as a source of current [8] [12].

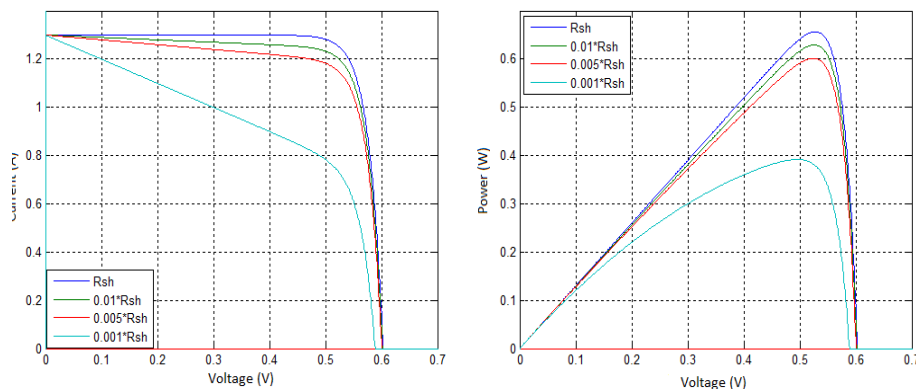


Figure 11: Influence of Shunt Resistance

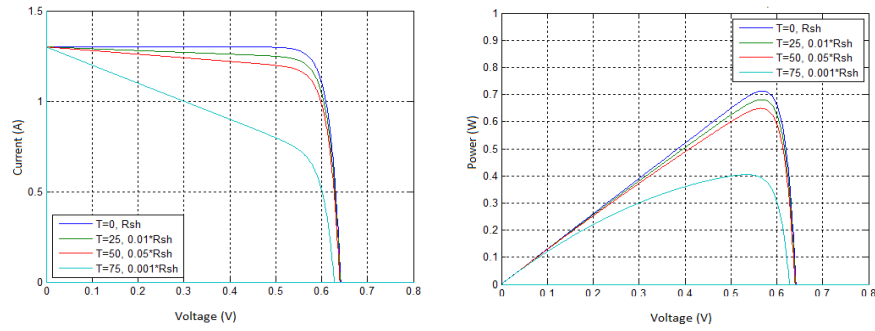


Figure 12: Influence of Shunt Resistance and Temperature

**Influence of Shunt and Series Resistances**

Figure 13 shows the effect of the two resistors series and parallel at the same time, where it can be concluded that the effect of the series resistance is negligible, relative to the shunt resistance. A minimization of the value of the shunt resistance induces an estrangement from the real operation of the cell [9].

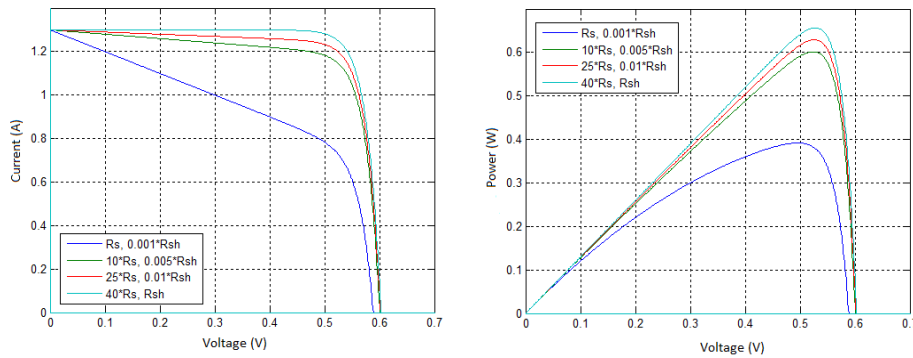


Figure 13: Influence of Shunt and Series Resistance

**Influence of Shunt Resistance and Irradiation**

Figure 14 presents the simultaneous influence of shunt resistance and the irradiation on a 1M5P model, from which we can collude that the I-V and P-V characteristics are similar to these of the shunt resistance influence shown in Figure 11, with the same values of short circuit current and open circuit voltage, so the shunt resistance influence in this case was been ignored relative to the irradiation influence.

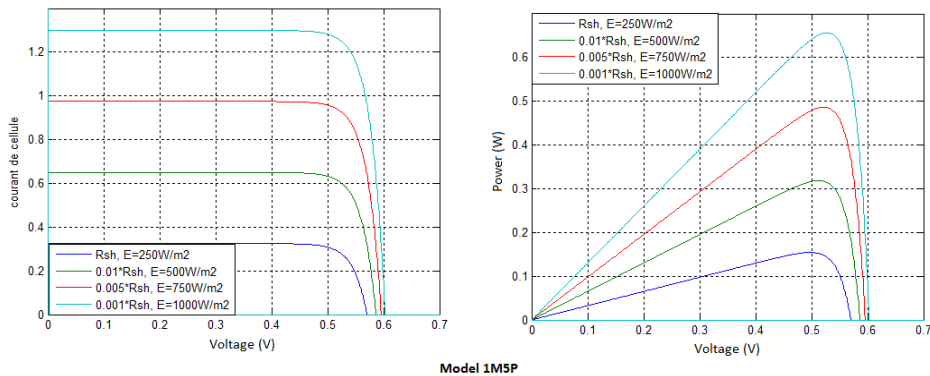
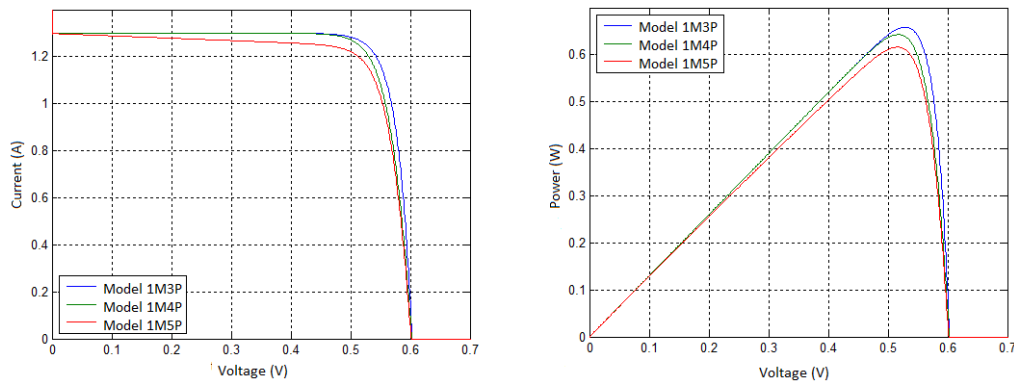


Figure 14: Influence of Shunt Resistance and Irradiation



## COMPARISON BETWEEN THE THREE MODELS

The same reference condition is selected for each model. The performance of the solar cell is normally evaluated in the test normalized conditions (STC), the irradiation is normalized to  $1000\text{W/m}^2$ , and temperature to  $25^\circ\text{C}$ . Figure 15 presents a comparison between different models of single diode PV cell from which we can note that 1M3P has the optimized performances of the single diode model with higher values of current and power, contrariwise the 1M5P gives the lower values of current and power, hence the 1M4P curves proves that it is the most accurate model since it is closer to the real operation of the PV cell [10] [13].



**Figure 15: Comparison between the Three Models of Single Diode PV Cell**

## CONCLUSIONS

In this paper we have presented the fundamental electric characteristics of photovoltaic cell of single diode where all the equivalent circuits were described, and the equivalent models were discussed. A comparison between these models demonstrated that the solar cell with series resistance model (1M4P) offers a more realistic behavior for the photovoltaic systems while it combines between the simplicity and the precision. The single diode model was analyzed in function of physical phenomena such as the resistance series and the resistance shunt, and the environmental parameters as the irradiation and the temperature.

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