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Electrical Modeling of a Silicon Photovoltaic Solar Cell: Comparative Study of Models Characterizing the Photovoltaic Solar Cell

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Abstract

In this article we make a detailed study and a presentation of the different models of circuit's equivalent to silicon-based photovoltaic solar cells. Starting from a real solar cell and real phenomena from the manufacture of the cell to the production of current by the cell. A comparison of the models with a real experimental method is carried out. The comparison is based on an overlay of the results. The study allowed us to choose the most suitable model. We are interested in the losses by leaks and the losses due to the development of the cell. In fact, we studied the influence of the shunt resistance on the current-voltage characteristic and the electrical power.

Keywords

Current Characteristic-Voltage, Photon Current, Electric model, Photocurrent, Photo Voltage, Electric Power, Semiconductor

1. Introduction

One of the clean and renewable energies is photovoltaic solar energy. It is an energy recovered and transformed directly into electricity from the sun's rays by photovoltaic solar cells. Energy is an essential source for life on earth, the more the energy challenge is sustainable development. There are fights that a country cannot win without sustainable access to energy. Photovoltaic energy is a way to solve the energy problem in many countries. This is why we are witnessing more and more the development of photovoltaic solar energy. Its development is linked to the performance of solar cells. The more profitable a salary panel is, the higher its conversion efficiency. This explains the multiple researches works in this field. Studies in the field of photovoltaic solar energy are increasingly taking an important place in physics. To make our contribution to studies and research in this field, we propose to study the current-voltage characteristics and the influence of the shunt resistance.

2. Theory

The current-voltage (I-V) characteristic can be used to identify the mechanisms and phenomena of conduction and/or diffusion and for the evaluation of the influence of the electrical parameters of the cell such as the series resistance (R_s), the resistance shunt (R_{sh}), the ideality factor n, the saturation current (I_s) and the width of the space charge region [1]. Early studies in this area showed that the conduction mechanism can be described by tunneling effect, Schottky effect or Poole-Frenkel effect [2] [3] [4]. Later studies of the I-V characteristic in the dark of a photovoltaic cell in forward bias as a function of the applied voltage have shown that, in regions of low voltage, a variation of the current can be translated by the Shockley equation [5].

Equation Shockley:

$$I = I_S\left[\exp\left(\frac{V}{V_T}\right)-1\right] \tag{2.1}$$

I_S is the saturation current

$$I_S = qAn_i^2\cdot\left(\frac{D_h}{L_hN_D}+\frac{D_e}{L_eN_A}\right) \tag{2.2}$$

So we have:

$$I = qAn_i^2\cdot\left(\frac{D_h}{L_hN_D}+\frac{D_e}{L_eN_A}\right)\left[\exp\left(\frac{V}{V_T}\right)-1\right] \tag{2.3}$$

With:

q: the elementary charge;

A: diode area;

D: diffusion coefficient;

L: diffusion coefficient;

V_T: thermal stress.

$$V_T = \frac{K_BT}{q}\quad [6] \tag{2.4}$$

The modeling of an equivalent electrical circuit necessarily involves mastering the physic cal behavior of each element of the equivalent circuit of the cell modelling. Several electrical models have been tested for studies of the photovoltaic cell. In this work a presentation and a study of these models have been carried out [7].

3. Two-Diode Model

The two (2) diode model is also called the two-exponential model.

Equivalent circuits of two-diode models are shown in **Figure 1**, **Figure 2** and **Figure 3**.

3.1. Model with Seven (7) Parameters

The seven (7) parameter model is also called 2M7P.

The photovoltaic cell is represented by the following electric circuit (**Figure 1**), which consists of a current source modeling the luminous flux, two diodes for the polarization of the cell, a shunt resistor and a resistor series.

- Intensity of the current supplied by the cell

$$I_{pv} = I_L - I_{D1} - I_{D2} - I_{sh} \quad (3.1)$$

$I_L = I_{ph}$: photon current;
I_{D1} : diode current 1;
I_{D2} : diode current 2;
I_{sh} : shunt resistor current.

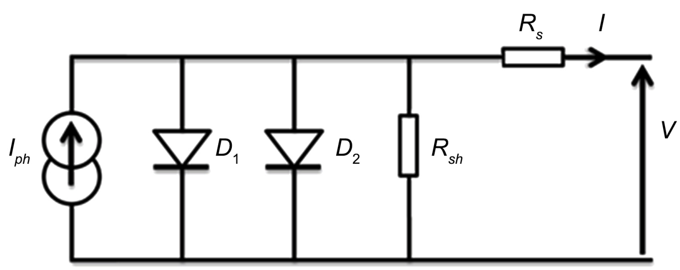

Figure 1. Model 2M7P.

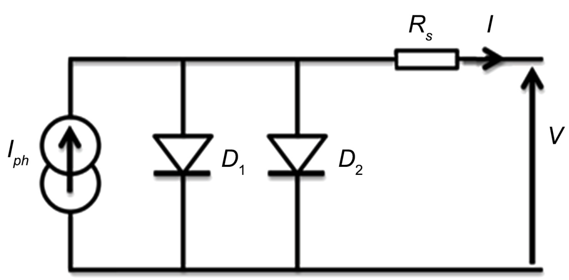

Figure 2. Model 2M6P.

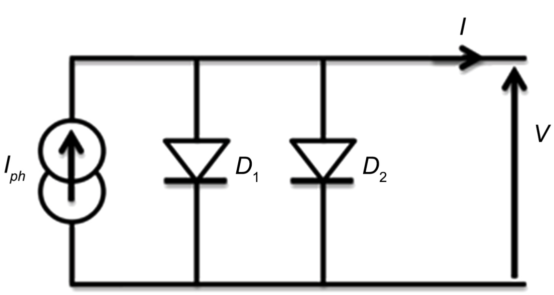

Figure 3. Model 2M5P.

$$I_{sh} = \frac{V_{p\upsilon} + I_{p\upsilon} R_S}{R_{SH}} \quad (3.2)$$

$$I_{D1} = I_{S1}\left(\exp\left(\frac{q}{\beta_1 kT}\left(V_{p\upsilon} + I_{p\upsilon} R_S\right)\right) - 1\right) \quad (3\text{-}3)$$

$$I_{D2} = I_{S2}\left(\exp\left(\frac{q}{\beta_2 kT}\left(V_{p\upsilon} + I_{p\upsilon} R_S\right)\right) - 1\right) \quad (3\text{-}4)$$

Equations (3.2), (3.3) and (4) in Equation (3.1) yield Equation (3.5)

$$I_{p\upsilon} = I_L - I_{S1}\left(\exp\left(\frac{q\left(V_{p\upsilon} + I_{p\upsilon} R_S\right)}{\beta_1 kT}\right) - 1\right) - I_{S2}\left(\exp\left(\frac{q\left(V_{p\upsilon} + I_{p\upsilon} R_S\right)}{\beta_2 kT}\right) - 1\right) - \frac{V_{p\upsilon} + I_{p\upsilon} R_S}{R_{SH}} \quad (3\text{-}5)$$

The parameters that go into Equation (3.5) are:

I_{S1} et I_{S2}: reverse saturation currents;

β_1 et β_2: the successive quality factors of diode 1 and diode 2;

R_S: resistance in series;

R_{SH}: shunt resistor.

3.2. Two-Diode Model without Shunt Resistor or 2M6P Model

The photovoltaic cell is represented by the electrical circuit (**Figure 2**), which consists of a current source modeling the luminous flux (illuminance), two diodes for the polarization of the cell and a series resistor. To pass from the model with seven (7) parameters to the model with six (6) parameters, we formulate the hypothesis that the cell is made in such a way that the losses by thermal leaks are negligible. Such an assumption in the modeling of the equivalent circuit means that the shunt resistor has a value which time towards infinity.

The photo-current $I_{p\upsilon}$ produced by the current source depends on the illumination and the series resistance R_S.

- Intensity of the current supplied by the cell

  In the 2M6P we have $R_{SH} \to \infty \quad \Rightarrow I_{sh} = 0$

  Equations (3.1) and (3.5) become:

$$I_{p\upsilon} = I_L - I_{D1} - I_{D2} \quad (3.6)$$

$$I_{p\upsilon} = I_L - I_{S1}\left(\exp\left(\frac{q\left(V_{p\upsilon} + I_{p\upsilon} R_S\right)}{\beta_1 kT}\right) - 1\right) - I_{S2}\left(\exp\left(\frac{q\left(V_{p\upsilon} + I_{p\upsilon} R_S\right)}{\beta_2 kT}\right) - 1\right) \quad (3.7)$$

3.3. Model at 2M5P

This model is obtained when we consider that the model with two (2) diodes is ideal, that is to say that we do not take into account the losses by leakage and the losses by Joule effect. These hypotheses result in a photo-current produced by a current source which depends on the illumination and the temperature.

- Intensity of the current supplied by the cell

We have:

$$R_{SH} \to \infty \quad \Rightarrow I_{sh} = 0 \quad \text{et} \quad R_S = 0$$

Equations (3.1) and (3.5) become:

$$I_{p\upsilon} = I_L - I_{D1} - I_{D2} \tag{3.8}$$

$$I_{p\upsilon} = I_L - I_{S1}\left(\exp\left(\frac{qV_{p\upsilon}}{\beta_1 kT}\right) - 1\right) - I_{S2}\left(\exp\left(\frac{qV_{p\upsilon}}{\beta_2 kT}\right) - 1\right) \tag{3.9}$$

4. Single Diode Model

The single diode module gives a simple representation of the solar cell reality. The one (1) diode model is also called the one exponential model. Actually there are several influences of parasitic resistances in the production of electrical energy, and the photovoltaic cell can be generally represented by the following diagrams:

The equivalent circuits of the one (1) diode models are shown in Figure 4, Figure 5 and Figure 6.

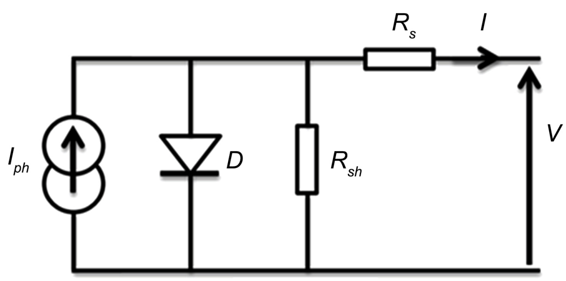

Figure 4. Model 1M4P.

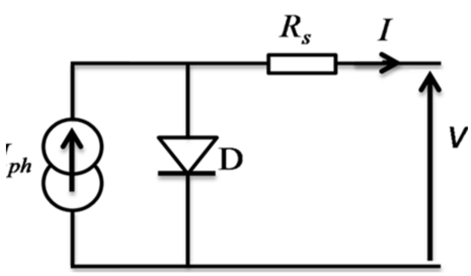

Figure 5. Model 1M3P.

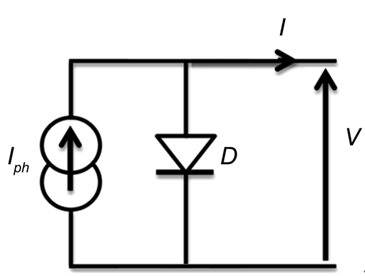

Figure 6. Model 1M2P.

4.1. Five-Parameter Diode Model or 1M5P Model

The photovoltaic cell is represented by the electric circuit (**Figure 4**). This is the most classic model in the literature. The model is also called a real diode model, it involves a current generator for modeling the incident light flux, a diode for the physical phenomena of polarization and two resistors (series and shunt).

These resistors will have some influence on the I-V characteristic of the solar cell:

1) The series resistance is the internal resistance of the cell; it mainly the resistance of the semiconductor used, the contact resistance of the collector grids and the resistivity of these grids.

2) The shunt resistance is due to a leakage current at the junction; it depends on how it was done.

- Intensity of the current supplied by the cell

The model is a diode so $I_{D2} = 0$

ID2 = 0 in equation (3.1) gives:

$$I_{p\upsilon} = I_L - I_{D1} - I_{sh}$$

The current generated by the photovoltaic cell is given by:

$$I_{p\upsilon} = I_L - I_{S1}\left(\exp\left(\frac{q\left(V_{p\upsilon} + I_{p\upsilon}R_S\right)}{\beta_1 kT}\right) - 1\right) - \frac{V_{p\upsilon} + I_{p\upsilon}R_S}{R_{SH}} \quad (3.10)$$

4.2. Four-Parameter Diode Model or 1M4P Model

The four-parameter model treats the PV cell as a current source, dependent on irradiance, connected in parallel with a diode in series with a series resistance R_s. The (**Figure 5**) models the equivalent circuit of the photovoltaic cell with four parameters to a diode.

The model is called 1M4P or one diode model without shunt resistance, it is a simple empirical electrical model, in the literature we are told that it is the closest model to the photovoltaic generator. It is a model that is currently widely used because of the quality of the results obtained.

This model makes use of the PV module specifications offered by the manufacturers, so it offers a very simple way to calculate the power produced by the PV modules.

- Intensity of the current supplied by the cell

The model is a diode so $I_{D2} = 0$,

and we have $R_{SH} \to \infty \Rightarrow I_{sh} = 0$.

So we get $I_{p\upsilon} = I_L - I_{D1}$.

The current generated by the photovoltaic cell is given by:

$$I_{p\upsilon} = I_L - I_{S1}\left(\exp\left(\frac{q\left(V_{p\upsilon} + I_{p\upsilon}R_S\right)}{\beta_1 kT}\right) - 1\right) \quad (3.11)$$

4.3. Model with a Three-Parameter Diode or Model 1M3P

It is the model of the ideal solar cell, the solar cell is a semiconductor component which delivers a current by exciting the latter by photons, so in first approximation we have a current source, which is short-circuited by a diode (because the solar cell is a p-n junction). This model is very idealistic, among the working conditions, diffusion phenomena are not taken into account. The equivalent diagram of the ideal photovoltaic cell includes a current generator which models the illumination and a diode in parallel which models the PN junction.

- Intensity of the current supplied by the cell

The model is a diode so $I_{D2} = 0$,

$$R_{SH} \to \infty \quad \Rightarrow I_{sh} = 0 \quad \text{and} \quad R_S = 0$$

So we get $I_{pv} = I_L - I_{D1}$.

The current generated by the photovoltaic cell is given by:

$$I_{pv} = I_L - I_{S1}\left(\exp\left(\frac{qV_{pv}}{\beta_1 kT}\right) - 1\right) \tag{3.12}$$

5. Conclusion

We have just presented the different equivalent circuit models characterizing a photovoltaic cell, which allowed us to simulate the models and obtain results for each model. The comparison of all these results with those obtained with a real cell, leads us to say that the two (2) diode models of the current-voltage characteristic are the most suitable models to take into account all the physical phenomena involved in the photovoltaic conversion process. Most among the two (2) models, the seven (7) parameter model is still the best fit. For the following, we will study the influence of the shunt resistance on the current-voltage characteristic and the power using the seven (7) parameter model [7].

6. Results and Discussions

6.1. Two (2) Seven (7) Parameter Model

The equivalent circuit is shown in **Figure 6**.

Under illumination, the current generated is expressed by:

$$I_{pv} = I_L - I_{S1}\left(\exp\left(\frac{q\left(V_{pv} + I_{pv}R_S\right)}{\beta_1 kT}\right) - 1\right) - I_{S2}\left(\exp\left(\frac{q\left(V_{pv} + I_{pv}R_S\right)}{\beta_2 kT}\right) - 1\right) - \frac{V_{pv} + I_{pv}R_S}{R_{SH}}$$

6.2. Influence of Shunt Resistance

6.2.1. Influence of the Shunt Resistance R_{SH} on the Characteristic I(A)

Figure 7 shows that the influence of the shunt resistor only decreases for high voltage values. The shunt resistance does not influence the intensity of the current in short-circuit, but slightly influences the value of the voltage in open circuit.

6.2.2. Influence of the Shunt Resistor Rsh on the Power

Figure 8 shows a difference in the maximum power when the shunt resistance increases. Maximum power increases with increasing shunt resistance and shifts slightly with voltage. The observed result is due to the fact that shunt currents are mainly due to current leakage along the edges of the cell, and these effects are minimized by building the module in a framework of good electrical insulators [8].

The results also show that the shunt resistance has a differential influence on the current-voltage characteristic compared to the power. The existence of cracks and complex structural defects becomes the seat of a physical phenomenon comparable to a shunt resistor, which appears in parallel on the electrical diagram. This shunt resistance is directly linked to the manufacturing processes, and its influence is only felt for very low values [9].

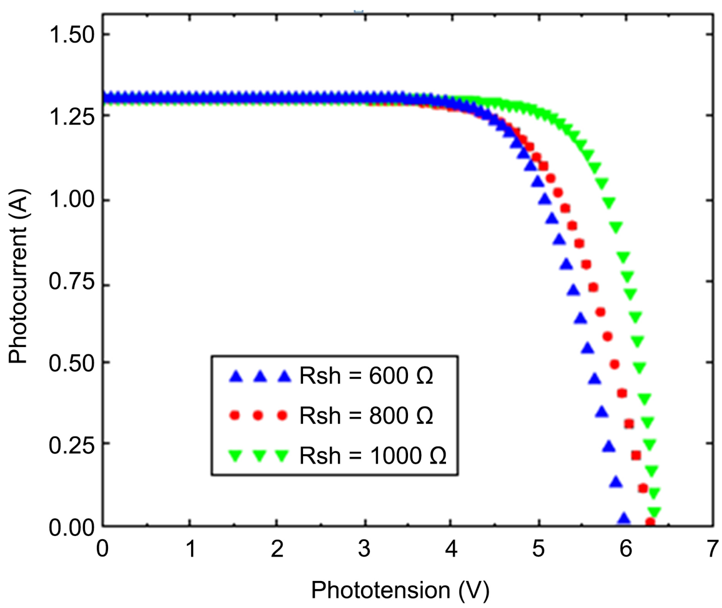

Figure 7. Influence of the shunt resistor on the current-voltage characteristic.

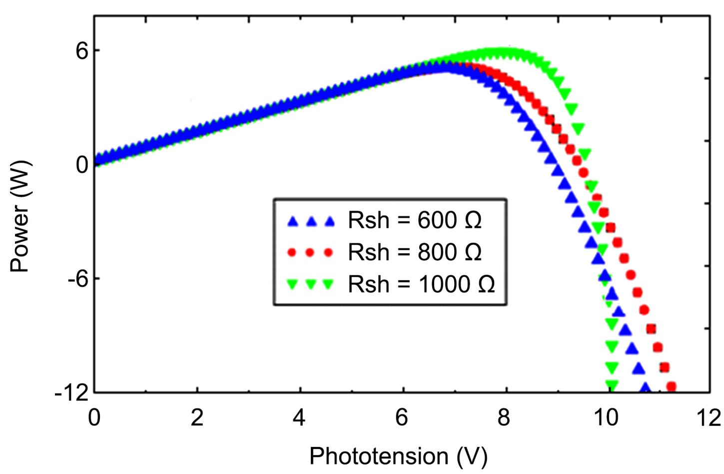

Figure 8. Influence of shunt resistance on power.

7. Conclusions

The comparative study of equivalent models seems interesting, modeling by equivalent circuits and their study makes it possible to retain a model among the six (6) models to translate a photovoltaic solar cell without being very idealistic. The influence of the shunt resistance on the current-voltage characteristic has been discussed.

We have chosen in this article a theoretical study to emphasize the expression of the current provided by the cell and the relationship between the existence of a parameter and its translation in the writing of the current provided. In perspective a comparative study of the series and shunt resistance of their influence on the performance of the solar cell.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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