

Determination of the Solar Cell Optimal Junction Recombination Velocity Using Hybrid Method

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Abstract: In this paper we present a technique for determining the optimum junction recombination velocity of a solar cell, using a combination of the electrical equivalent model, and the finite element method. Starting from the continuity equation that describes the solar cell operation solved in one dimension by the finite element method, the excess minority carrier's density is determined. From this density, the photocurrent, the photovoltage and the power produced by the solar cell are determined. The photocurrent and the photovoltage are represented according to the junction recombination velocity, as well as the solar cell power versus the photovoltage, for various values of the series resistance. In considering its equivalent electrical model, the solar cell is modeled and simulated with Matlab/Simulink. In this simulation model, the capacitor initially discharged, charges under the effect of the solar cell. Its impedance varying according to time, represents the load resistance which corresponds to an operating point of the solar cell. During the capacitor charge process for various values of the series resistance, we obtain the current-voltage characteristic of the solar cell in order to highlight the series resistance effects on the solar cell power. From the optimal value of the power, and that of solar cell photovoltage obtained by simulating the solar cell using Matlab/Simulink, the value of the junction recombination velocity corresponding to the maximum value of the solar cell power is determined numerically, for various values of the series resistance.

Keywords: Solar Cell, Junction Recombination Velocity, Finite Element, Series Resistance, Photocurrent, Photovoltage, Optimal Power

1. Introduction

Since a few decades, several studies are carried out in order to improve solar cells' performances. These studies based for most cases on the analytical methods, permit to highlight the effects of the phenomenological parameters, such as diffusion length, illumination level, junction and back surface recombination velocities, on solar cell electrical parameters [1-4]. Several techniques for solar cells' parameters determination have been elaborate such as Short-Circuit Current Insertion Technique (TICCC) [1, 3], Short-Circuit Current Ratio Technique (TRCCC) [5, 6], open Circuit Voltage Curve Insertion Technique (TICTCO) [7].

These techniques based on analytical methods, present some limits in solving some equations. Nowadays one uses more and more numerical methods such as the finite element method, characterized by its robustness and flexibility in its implementation [8-12].

In this paper, we present a technique for determining the optimal junction recombination velocity of a solar cell, based on a method combining the finite element method and the solar cell electrical equivalent model. This approach permits to determine the optimal junction recombination velocity of a solar cell under multispectral steady state Illumination, and highlights series resistance effects on the solar cell power.

2. Theoretical Study

2.1. Excess Minority Carriers' Density Determination Using Finite Element Method

Let us consider a solar cell illuminated on its front surface such as shown in figure 1.

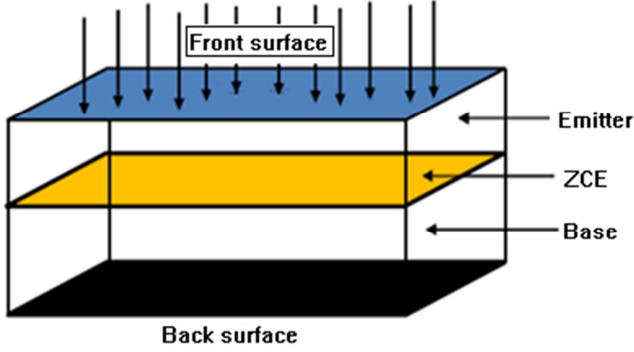


Figure 1. Solar cell illuminated on its front face.

The continuity equation which governs the solar cell operating in considering only excess minority carriers density photogenerated in the base, is a differential equation which may be represented with its boundary conditions as follow [8, 9, 13]

$$\begin{cases} -\frac{\partial^2 \delta(x)}{\partial x^2} + \frac{\delta(x)}{L^2} = \frac{g(x)}{D} \\ \delta'(0) = \frac{S_j}{D} \cdot \delta(0) \\ \delta'(H) = -\frac{S_b}{D} \cdot \delta(H) \end{cases} \quad (1)$$

S_j indicates the junction recombination velocity, S_b the back surface recombination and H , the base depth. L represents the diffusion length, D , the diffusion coefficient and $g(x)$ the generation rate of carriers' charge. When the solar cell is illuminated by its front surface, the generation

rate $g(x)$ is given by [14-16]:

$$g(x) = \sum_1^3 n \cdot a_i \exp(-b_i x) \quad (2)$$

n represents the illumination level. The parameters a_i and b_i are the constants deduced from the modeling of the generation rate considered for the overall solar radiation spectrum [1, 2, 3, 10]. x indicates the depth in the base such as $x=0$ at the junction and $x=H$ at the back face.

This continuity equation is an elliptic differential equation with Fourier and Neumann boundaries conditions [9-11], and can be written in the following form:

$$\begin{cases} -u''(x) + c \cdot u(x) = f(x) \\ u'(0) = a \cdot u(0) \\ u'(H) = b \cdot u(H) \end{cases} \quad (3)$$

With:

$$a = \frac{S_j}{D}; \quad b = \frac{S_b}{D}; \quad c = \frac{1}{L^2} \quad \text{and} \quad f(x) = \frac{g(x)}{D}$$

$u(x)$ is the unknown numerical function to determine by the finite element method.

To solve Equation (3), one assimilates the solar cell base and its depth H , to a domain $[0, H]$. This domain is subdivided in N finite elements as represented in figure 2.

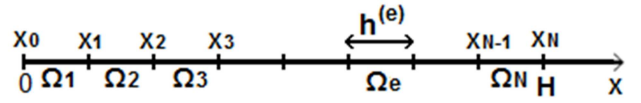


Figure 2. Discretization in finite elements of the solar cell base depth.

Using the Galerkin method to obtain the variational form of the equation (3a), we multiply this equation by a test function $v(x)$ and integrate over the domain $[0, H]$. We obtain:

$$-\int_0^H \frac{d}{dx} \left(\frac{d}{dx} u(x) \right) v(x) dx + \int_0^H c(x) u(x) v(x) dx = \int_0^H f(x) v(x) dx \quad (4)$$

Integration by part of the first term leads to:

$$\int_0^H \frac{d}{dx} u(x) \frac{d}{dx} (v(x)) dx - [u'(x) v(x)]_0^H + \int_0^H c(x) u(x) v(x) dx = \int_0^H f(x) v(x) dx \quad (5)$$

The equation (5) can be written formally in the following form:

$$A(u, v) = L(v) \quad (6)$$

where

$$A(u, v) = \int_0^H \frac{d}{dx} u(x) \frac{d}{dx} (v(x)) dx - [u'(x) v(x)]_0^H + \int_0^H c(x) u(x) v(x) dx \quad (7)$$

and

$$L(v) = \int_0^H f(x) v(x) dx \quad (8)$$

After assembly of all the finite elements, the variational form can be written in matrix form as:

$$A_u U = L_u \quad (9)$$

The carriers' charge density is given by:

$$U = A_u^{-1} L_u \quad (10)$$

2.2. Photocurrent Density of and Photovoltage

The photocurrent density and the photovoltage are respectively, given by:

$$J = qD \frac{\partial \delta(x)}{\partial x} \Big|_{x=0} \quad (11)$$

and,

$$V = V_T \ln \left(\frac{N_b}{N_i^2} \delta_\alpha(0) + 1 \right) \quad (12)$$

with q the elementary charge. $V_T = \frac{KT}{q}$ indicates the thermal voltage, K , the Boltzmann constant and T , the absolute temperature.

Knowing the value of the photovoltage, one can determine I_{ph} with the aid of equation (11), value which is used in the equivalent electrical model of the solar cell as represented in figure 3 [2].

2.3. Solar Cell Modeling

The electrical equivalent model of the solar cell is depicted in figure 3 with Matlab/Simulink.

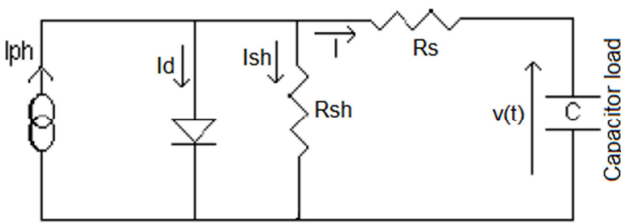


Figure 3. Electrical equivalent model of a solar cell under constant illumination.

As shown in figure 3, this equivalent electrical model

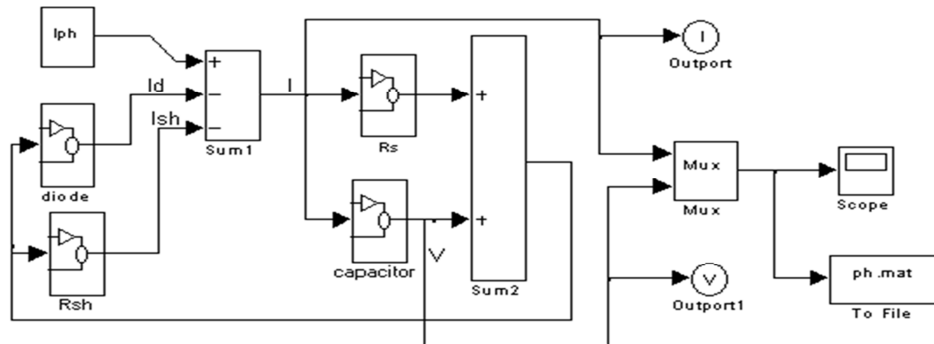


Figure 4. Simulation model of the solar cell under constant illumination.

In addition to the elements modeled above, this simulation model contains two outputs namely *output* and *output1* which permit to collect the current I and the voltage V respectively.

3. Results and Discussions

3.1. Determination of the Photovoltage Versus the Junction Recombination Velocity

From the numerical codes conceived with Matlab using the

contains a current generator I_{ph} , connected in parallel with a perfect diode crossed by a current I_d ; a shunt resistance R_{sh} which materializes the loss of current loss by carrier's recombination at the junction; a series resistance R_s due to the voltage drop and ohmic contacts. The capacitor with its capacitance C , represents the load which defines the operating point of the solar cell. It permits to obtain the solar cell current-voltage characteristic [2].

In order to simulate the variation of the solar cell operating point through the current-voltage characteristic, the capacitor initially discharged, with its voltage $v(t)=0$, charges under the effect of the solar cell. Its impedance varying according to time, represents the load resistance, which corresponds to an operating point of the solar cell.

Thus at the initial moment, the capacitor is discharged this case corresponds to a short-circuit operation. When it is completely charged, the current is equal to zero and that corresponds to an operation in open circuit of the solar cell. Like this, during the charging process of the capacitor, the solar cell operating point scans the current-voltage characteristic from the short-circuit operating point to the open circuit operating point [2].

The elements contained in the electrical equivalent model of the solar cell, are thus modeled and simulated using the Matlab/Simulink software to obtain the maximum power which permits to determine the optimal junction recombination velocity.

For the simulation with Matlab/Simulink, the current generator I_{ph} is modelled by a constant current generator.

Assembly in Matlab/Simulink of all these elements of the electrical equivalent model of the solar cell leads to a simulation model of the solar cell under constant illumination, represented in figure 4.

finite element method, we have determined numerically, the photovoltage according to the junction recombination velocity, after assembling the matrix A_u and L_u , where only the base contribution is taken into account. After studying the convergence of these numerical solutions, we have obtained the photovoltage according to the junction recombination velocity S_j , as represented in figure 5.

This curve is used as abacus to determine graphically, the optimal junction recombination velocity of the solar cell.

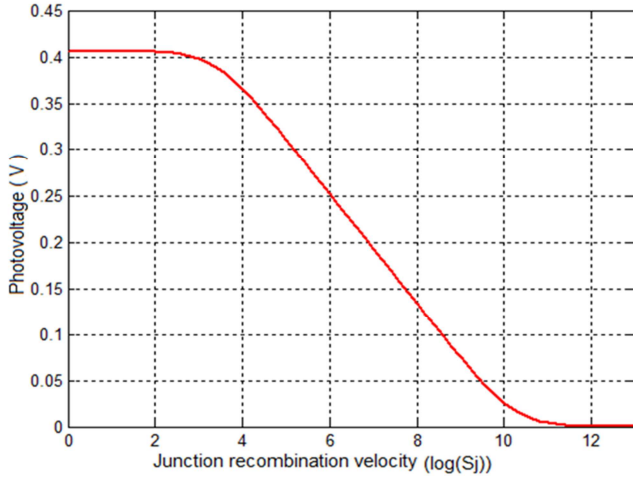


Figure 5. Photovoltage versus junction recombination velocity: S_j , $D=26\text{cm}^2/\text{s}$; $L=0,01\text{ cm}$, $S_b=10^3\text{cm/s}$.

As shown in this figure, for low values of the junction recombination velocity S_j , the photovoltage is constant and corresponds to the open circuit photovoltage. Then it decreases until to cancel each other out when the short-circuit operation is reached.

3.2. Photocurrent and Photovoltage

The simulation model described above in figure 4 allows us to obtain values of the photovoltage and the photocurrent delivered by the solar cell, during the capacitor charging process. Thus we have represented the photocurrent and the photovoltage delivered by the solar cell, with a value of series resistance $R_s=0$, in figures 6 and 7 respectively.

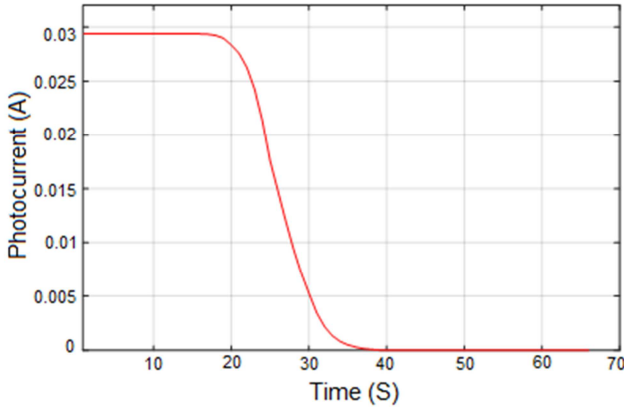


Figure 6. Photocurrent.

We can note that for the low values of time between 0 and 15s approximately, the photocurrent through the capacitor is constant and close to 30mA. Then it decreases and is cancel each other out around 40mA when the capacitor is completely charged.

The photovoltage is also represented in figure 7 below.

It is noted that, the photovoltage increases according to time and reaches a constant value corresponding to the open circuit photovoltage V_{co} around 0,6V at the end of a time t close to 30s.

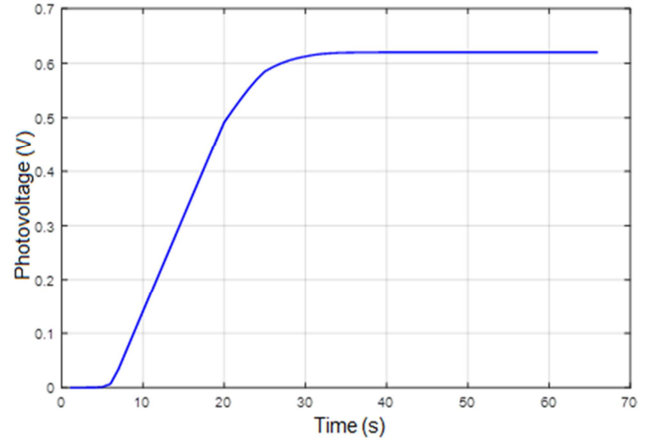


Figure 7. Photovoltage.

3.3. Caractéristique Courant-tension

Given at each time step we have a value of the photocurrent and a value of photovoltage corresponding to the solar cell operating point during capacitor charge process, one can obtain the current-voltage characteristic of the solar cell.

Thus, for various values of series resistance R_s , the current-voltage characteristic and the power produced by the solar cell, are represented respectively in figures 8 and 9.

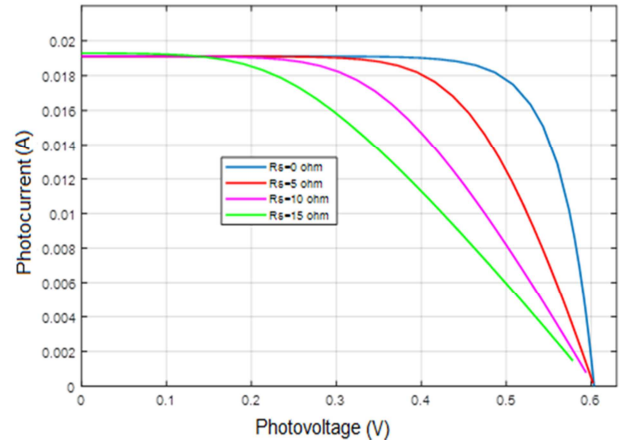


Figure 8. current-voltage characteristic for various values of the series résistance.

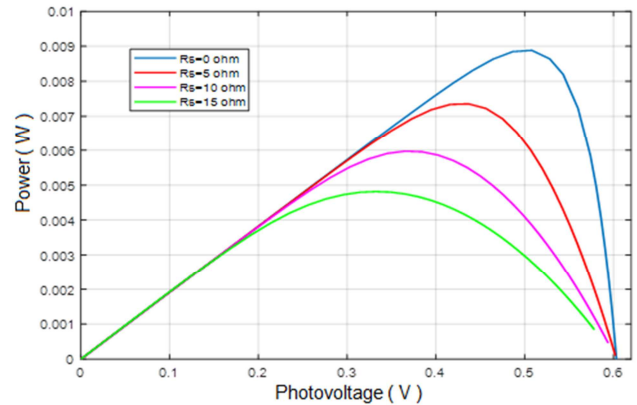


Figure 9. Power versus photovoltage for various values of R_s .

As waited, one can note that the series resistance R_s has an effect on the current-voltage characteristic of solar cell, which is revealed by the reduction of the fill factor, when R_s increases. This effect is also noticed on the power of the solar cell represented below, for various values of the series resistance.

The curves of figure 9 present a maximum when the photovoltage increases. This maximum power corresponds to an optimal junction recombination velocity S_{jop} , associated to the optimal operation of the solar cell [2].

3.4. Determination of the Optimal Junction Recombination Velocity

From the electrical equivalent model of the solar cell and for various values of R_s , one determines the maximum power P_{max} delivered by the solar cell, the open circuit photovoltage V_{co} and the photovoltage V_{opt} corresponding to P_{max} . Given that the solar cell is represented by a current generator, the short-circuit photocurrent I_{ph} is known. In the numerical computer code of the finite elements model, one gives to V_{co} , and I_{ph} the values determined from the Simulink model. The optimal junction recombination velocity S_{jop} is thus numerically obtained.

The results obtained are shown in the following table:

Table 1. Table of numerical values of the optimal junction recombination velocity.

R_s (Ω)	0	5	10	15
P_{max} (mW)	8.90	7.40	6.00	4.80
V_{opt} (V)	0.507	0.436	0.385	0.335
S_{jop} (cm/s)	$2.52 \cdot 10^4$	$1.58 \cdot 10^5$	$6.30 \cdot 10^5$	$2.51 \cdot 10^6$

As expected, these results show that series resistance has an effect on the power and the optimal point operating point of the solar cell. The higher it is, the more the junction recombination velocity S_{jop} corresponding to the maximum power is great. That can be explained on the one hand, by the fact that the junction recombination velocity being composed of two components [2, 6, 7] namely the intrinsic junction recombination velocity S_{jo} , and the recombination velocity S_F , and on the other hand, by the increase in R_s revealing the deterioration of the quality of material; the increase in R_s causes the increase in the ohmic losses and thus the increase in S_{jo} . Losses being enormous, the power delivered by the solar cell decreases and the optimum power is obtained with great values of the junction of recombination velocity S_j .

4. Conclusion

In this study we presented a method allowing to determine the optimal junction recombination velocity of a solar cell, by highlighting the series resistance effects on the junction recombination velocity.

After solving the continuity equation using finite element method, a numerical solution of the photogenerated carriers' charge density has been obtained. This carriers' charge density has served to determine the photocurrent and the photovoltage according to the junction recombination velocity S_j . Knowing

the maximum value of the power produced by the solar cell, the short-circuit photocurrent, open circuit photovoltage obtained starting from the electrical equivalent model of the solar cell, and adapted to the theoretical numerical values, the optimal junction recombination has been determined.

These results being in accordance with those obtained previously by the other authors, this study based on numerical simulations, can continue by analyzing the effects of other parameters like shunt resistance, and by making experimental measures.

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