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Modeling the Behavior of a Photovoltaic Generator Using a Four-Parameter Electrical Model

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Abstract: Photovoltaic solar energy consists of the direct conversion of sunlight into electricity by means of solar cells. These cells, electrically interconnected in series and/or in parallel, form the photovoltaic generator (GPV). The efficiency of the GPV is influenced by the irradiation and the temperature. In the intertropical zone, these two atmospheric factors vary rapidly and considerably influence the efficiency of the photovoltaic generator. This paper highlights the characteristics of the four-parameter cell photovoltaic generator when these two parameters (irradiance and/or temperature) vary rapidly. The simulation results obtained with the MATLAB/SIMULINK software show that with the four-parameter model the response time of the generator is proportional to the variation of the irradiance, i.e. the irradiance perturbation has an almost instantaneous effect on the current delivered by the photovoltaic generator and, when the temperature increases, the maximum power decreases, which confirms the correlation between these parameters. In fact, it can be seen that the developed model gives results close to the values provided by the manufacturers (five parameters) for amorphous, monocrystalline and polycrystalline cells with relative errors varying between 0.015 and 1.26%. The response time of the PV generator obtained with this model is 2 ms. The evaluation of the simulation method was also performed.

Keywords: Photovoltaic Generator, Irradiance, Temperature, Parameter

1. Introduction

For a very long time, man has been trying to use the energy emitted by the sun. Most of the uses are direct, such as in agriculture, through photosynthesis, or in the various applications of drying and heating, as well as industrial [1]. This energy is available in abundance over the entire surface of the earth and, despite a significant attenuation when crossing the atmosphere, the remaining quantity remains important when it reaches the ground. It is possible to estimate 1000W/m² in temperate zones and up to 1400W/m² when the atmosphere is not polluted with dust or water [2-4]. The solar flux received at ground level depends on: the orientation, nature and inclination of the earth's surface; the latitude of the location, its degree of pollution and its altitude; the time of year; the time of day; the nature of the cloud layers. Thus, there are areas in the world that are more favored than others from the point of view of sunshine [3].

The main physical phenomena mentioned above are parameters to be taken into account for the installation and maintenance of photovoltaic generators. Indeed, the behavior of these energy generators is more or less random, depending on the installation site. Thus, if we consider areas with a dry climate and a high sunshine level during the year, the solar flux can be easily moderated and predictable according to the hours of the day and the days of the year [4, 5]. The operation of PV generators is then often close to the estimated one. If, on the contrary, one considers more unfavorable areas, often ventilated and with cloudy weather alternating with sunny periods on several days per year, the irradiation changes rapidly and in large proportions [6-8]. It is difficult to make accurate predictions of the irradiance at a particular place and time.

In intertropical areas where the sun shines abundantly and where there is a large rural population without infrastructure to equip itself with an electrical network and without real access to appropriate health and education services, photovoltaic generators present a clear advantage to have electrical energy [5]. However, these photovoltaic generators are highly dependent on climatic conditions, namely irradiance and temperature [9-12]. In fact, these two parameters strongly influence the output I-V characteristic of the photovoltaic system. In order to take this influence into account, researchers have implemented the study of other solar cell model [13, 14] in order to facilitate the optimization of the maximum power point tracking MPPT [15]. Indeed, in these regions, there is a rapid variation of these parameters and this can lead to an operation below the nominal operating point of the photovoltaic generator.

The problems that remain to be solved concern both the conversion equipment, which is still expensive, and the conversion chain, which has many losses due to non-optimization and often inappropriate use of static converters. In the field of conversion systems, research can be summarized in two points:

1) The development of an exact mathematical model which represents the real photovoltaic cell, and which reflects the influence of the different atmospheric conditions on the parameters of the solar cell [16-21].
2) The development of an effective electrical model which makes it possible to determine the maximum point of power of the characteristic I (V) of the cell for any condition of illumination and temperature, and a few either the nature of change of these Fast or slow conditions.

In this work, we determine the response time of a photovoltaic generator as a function of irradiance and surface temperature of the photovoltaic module.

In this work, we use, the constant parameter model, the Newton Raphson method, and the MATLAB/SIMULINK software. The work revolves around three sections:

In the first, we present general concepts on photovoltaic energy, the principle of the search of the maximum power point, the influence of the operating conditions (illumination, temperature), and the different electrical models existing in the literature.

In the second section, the method of modeling the PV generator using the four-parameter electrical model is detailed so that it can be implemented in MATLAB/SIMULINK.

In the third section, we present the results obtained during the simulation to validate the model used.

2. Modeling the Photovoltaic Generator Using a Four-Parameter Electrical Model

The photovoltaic generator is a non-linear device, usually described by its characteristics I-V and by the equivalent circuit [11, 17]. There are several types of equivalent circuits of the photovoltaic cell in the literature [22, 23] as presented in the chapter precede. In this chapter we will formulate the equivalent circuit of a photovoltaic cell with a single exponential (four-parameter model), as a result of implementing this model in Matlab Simulink.

2.1. Photovoltaic Generator Modeling (GPV)

In this work, we used the model at an exponential (four-parameter model). The photovoltaic module is characterized by its equivalent electrical diagram that consists of a current source that models the conversion of the light flow into electrical energy, a series resistor RS representing the various contacts and connection resistors, a parallel diode that models that models that models PN junction [19].

In this work, we have used the one exponential model (four parameters model). The photovoltaic module is characterized by its equivalent electrical schematic, which consists of a current source that models the conversion of the luminous flux into electrical energy, a series resistor RS representing the different contacts and connection resistors, a parallel diode that models the PN junction [19].

2.2. Photovoltaic Module

The photovoltaic generator consists of a photovoltaic panel. The goal is to establish the model to implement in Matlab/Simulink; and then to find by simulation the characteristics (I-V and P-V) of this generator as well as its behavior according to the solar parameters namely the illumination in the plane of the panel G and the temperature T.

2.3. Choice of the Model

In general, the choice of a model always depends on the intended use, but also on the information available to determine the parameters. If only the data provided by the manufacturer is available, it is usually not possible to determine more than four parameters. In this case, it is easiest to take a 4-parameter model (without parallel resistance) and use the available information to determine [6]:

1) the photonic current; I_L
2) the leakage current of the junction; I_0
3) the imperfection coefficient of the diode; γ
4) the series resistance of the cell; R_S

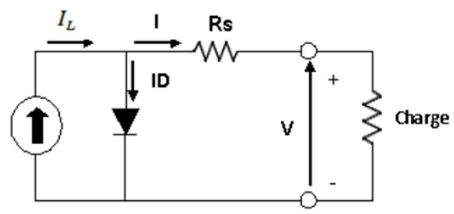

Figure 1. *Equivalent pattern of the model.*

2.3.1. Determination of Electrical Parameters

According to figure 1, and applying Kirchhoff's law, the output current deduced from the equivalent diagram is the following:

$$I = I_L - I_D \quad (1)$$

1) Calculation of I_L

The photon current is linked to the illumination, temperature and photonic current measured under reference conditions by W. De Soto [1]:

$$I_L = \frac{G}{G_{REF}}\left[I_{L,REF} + \mu_{ISC}\left(T_c - T_{C,REF}\right)\right] \quad (2)$$

To simplify the calculation of I_L, we make the approximation that the current $I_{L,REF}$ is equal to the short-circuit current, $I_{SC,REF}$ of the module [3].

2) Calculation of I_D

The diode current is given by the Shockley equation [4].

$$I_D = I_0\left(\exp\left(\frac{q\left(V + IR_s\right)}{\gamma k T_C}\right) - 1\right) \quad (3)$$

3) Calculation of I_0

The reverse saturation current of the diode is expressed as a function of the characteristics of the material and the temperature as follows [3]:

$$I_0 = DT_c^3 \exp\left(\frac{-q\varepsilon_G}{AkT_c}\right) \quad (4)$$

The saturation reverse current I_0 is calculated by taking the ratio of equation (23) at two different temperatures, thereby eliminating the D factor. As with the determination of I_L, I_0 is related to temperature and saturation current defined at reference conditions by the following relationship:

$$I_0 = I_{0,REF}\left(\frac{T_c}{T_{c,REF}}\right)^3 \exp\left[\left(\frac{q\varepsilon_G}{kA}\right)\left(\frac{1}{T_{c,REF}} - \frac{1}{T_c}\right)\right] \quad (5)$$

The characteristic I (V) is thus described by:

$$I = I_L - I_0\left[\exp\left(\frac{q\left(V + IR_s\right)}{\gamma k T_c}\right) - 1\right] \quad (6)$$

The quality factor γ measures the imperfection of the cell and is related to the fulfillment factor as follows γ = A.NCS.NS, NCS is the number of cells connected in series per module.

2.3.2. Resolution of the Characteristic Equation I(V)

After having determined the various parameters of the equivalent circuit, it is possible to solve the equation of the characteristic *I(V)*, by iterative numerical methods (the dichotomy method, the Lagrange method, the fixed point method and the method of Newton Raphson) for a given illumination and a modulus temperature, the set of unknown parameters which are (I_L, I_0, γ, *Rs*), then the other unknown variables in the original equation I(V) which are I and V of module [4]. Newton's method is chosen for the rapid convergence of the response.

2.4. Newton's Method

Newton Raphson's method is one of the most widely used methods for solving nonlinear equations. The algorithm of this method is based on the use of the Taylor expansion.

Consider an equation to be solved of the form:

$$f(x) = 0 \quad (7)$$

From a value of an initial value of the solution, we seek a correction such that:

$$0 = f\left(x_0 + \delta x\right) \quad (8)$$

By doing a Taylor expansion around $x = x_0$, we find:

$$0 = f(x_0) + f'(x_0).\delta x + \left(\frac{f''(x_0)\delta x^2}{2!}\right) + \left(\frac{f'''(x_0)\delta x^3}{3!}\right) + \ldots \quad (9)$$

It is now sufficient to neglect the terms of order greater than or equal to 2 in δx to obtain:

$$f(x_0) + f'(x_0).\delta x \approx 0 \quad (10)$$

We can then isolate the desired correction:

$$\delta x = \frac{f(x_0)}{f'(x_0)} \quad (11)$$

The correction δx is in principle the quantity that must be added to cancel the function $f(x)$ since we have neglected the terms of order greater than or equal to 2 in the Taylor development, this correction is not perfect and we pose:

$$x_1 = x_0 + \delta x \quad (12)$$

So

$$x_{i+1} = x_i - \frac{f(x)}{f'(x)} \quad (13)$$

With

$f'(x)$: is the derivative of the function $f(x)$

$f(x) = 0$, x_i , is a current value and x_{i+1} is a next value.

The rearrangement of the equation I (V) gives the following function [3]:

$$f(I) = I_L - I - I_0\left[\exp\left(q\left(\frac{V + IR_S}{\gamma KT}\right)\right)\right] \quad (14)$$

Substituting this equation into equation [5] gives the following equation, and the Output Current *I* is calculated iteratively [3].

$$I_{n+1} = I_n - \frac{I_L - I_n - I_0\left[\exp\left(q\left(\frac{V + I_n R_s}{\gamma KT}\right)\right)\right]}{-1 - I_0\left(\frac{qR_s}{\gamma KT}\right)\exp\left(q\left(\frac{V + I_n R_s}{\gamma KT}\right)\right)} \quad (15)$$

2.4.1. Evaluation of Series Resistance Rs

The series resistance (R_S) of the PV module has a great impact on the slope of the I-V curve, therefore the value of R_S is calculated by evaluating the *dI/dV* slope of the I-V curve at the V_{OC} point. The R_S equation is obtained by equation [3].

$$R_s = -\frac{dI}{dV} = \frac{\gamma KT / q}{I_0 \times \exp\left(q\left(\frac{V + IR_S}{\gamma KT}\right)\right)} \quad (16)$$

Then, from equation (4), the value of Rs is estimated as a function of $V_{co} = V$.

$$R_s = -\frac{dI}{dV}\Big|_{VCO} = \frac{\gamma KT / q}{I_0 \times \exp\left(\left(\frac{qV_{co}}{\gamma KT}\right)\right)} \quad (17)$$

2.4.2. Determination of Maximum Power Parameters

At the maximum power point we have:

$$\frac{\partial P}{\partial V} = V\frac{\partial I}{\partial V} + I = 0 \quad (18)$$

The current being described by equation [10], the partial derivative of *I* as a function of the voltage *V* is:

$$\frac{\partial I}{\partial V} = -I_0 \exp\left(\frac{q(V + IR_S)}{kT_{C,REF}\gamma}\right) \times \frac{q}{kT_{C,REF}} \times \left(1 + R_S\frac{\partial I}{\partial V}\right) \quad (19)$$

An explicit expression for $\frac{\partial I}{\partial V}$ is obtained simply by rearranging equation (19). Substituting this expression into (18) and replacing *I* by I_{MP} and V by V_{MP} gives us:

$$I_L + I_0 \exp\left(\frac{q(V_{MP} + I_{MP}R_S)}{kT_{C,REF}\gamma}\right) \times \left(1 + \frac{\frac{qV_{MP}}{kT_{C,REF}\gamma}}{1 + \frac{qR_S I_0}{kT_{C,REF}\gamma}\exp\left(\frac{q(V_{MP} + I_{MP}R_S)}{kT_{C,REF}\gamma}\right)}\right) = 0 \quad (20)$$

To eliminate V_{MP} in equation (20), the general equation of *I(V),* is used in which we replace *I* by I_{MP} and *V* by V_{MP}. Rearranging this equation gives V_{MP}:

$$V_{MP} = \frac{kT_{c,REF}\gamma}{q}\ln\left(\frac{I_L - I_{MP}}{I_0} + 1\right) - I_{MP}R_S \quad (21)$$

An explicit expression for I_{MP} is obtained by substituting equation (6) into equation (11):

$$I_{MP} + \frac{(I_{MP} - I_L - I_0)\left[\ln\left(\frac{I_L - I_{MP}}{I_0} + 1\right) - \frac{I_{MP}R_S q}{kT_{C,REF}\gamma}\right]}{1 + (I_L - I_{MP} + I_0)\frac{R_S q}{kT_{C,REF}\gamma}} = 0 \quad (22)$$

Newton Raphson's method is applied to solve I_{MP} using the following initial value:

$$I_{MP,GUESS} = \frac{G}{G_{REF}} NP\left(I_{MP,REF} + \mu_{ISC}\left(T_c - T_{C,REF}\right)\right) \quad (23)$$

Once I_{MP} is obtained, V_{MP} can be calculated using equation (21). Thus the current and the voltage at the maximum power point are determined for a given temperature and illumination.

For given illumination, temperature and cell parameters, the relationship of current versus voltage is given by: $I = I_L - I_0\left[\exp\left(\frac{q(V + IR_s)}{\gamma kT_C}\right) - 1\right]$ which is an implicit nonlinear equation and must be solved numerically.

3. Results and Discussion

3.1. Validation of the Developed Model

The three types of PV cells were used to evaluate the efficiency of the model.

3.1.1. Amorphous Cells

The comparison between the simulation and the data provided by the manufacturer is illustrated in Table 1, where the simulation results of the four-parameter model are compared with the results provided by the manufacturer.

It can be noted that: the average relative error on the voltage corresponding to the maximum power is 0.36% and the average relative error on the maximum power is 0.015%.

Table 1. *Comparison between the developed model and the manufacturer's data (PW500 from PHOTOWATT, amorphous).*

Conditions	Data provided by the manufacturer	Model result	Relative error (%)
Temperature 50°C	P_{MP} = 60.48W	P_{MP} = 60.48W	0.00% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 14.60V	V_{MP} = 14.61V	0.00% for V_{MP}
Temperature 25°C	P_{MP} = 70.00W	P_{MP} = 70.00W	0.00% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 16.50V	V_{MP} = 16.50V	0.00% for V_{MP}
Temperature 0°C	P_{MP} = 77.78W	P_{MP} = 77.78W	0.01% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 18.40V	V_{MP} = 18.31V	0.48% for V_{MP}
Temperature 75°C	P_{MP} = 85.75W	P_{MP} = 85.80W	0.05% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 20.30V	V_{MP} = 20.11V	0.93% for V_{MP}

3.1.2. Polycrystalline Cells

The comparison between the simulation and the practical data is illustrated in Table 2. It can be noticed that: the average relative error on the voltage corresponding to the maximum power is 1.26% and the average relative error on the maximum power is 0.16% for the model

Table 2. *Comparison between the model developed and the manufacturer's data (PW500 from PHOTOWATT, polycrystalline).*

Conditions	Data provided by the manufacturer	Model result	Relative error (%)
Temperature 50°C	P_{MP} = 50.00W	P_{MP} = 50.3431W	0.28% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 14.60V	V_{MP} = 14.94V	1.32% for V_{MP}
Temperature 25°C	P_{MP} = 36.00W	P_{MP} = 36.06W	0.16% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 16.50V	V_{MP} = 16.76V	0.57% for V_{MP}
Temperature 0°C	P_{MP} = 40.05W	P_{MP} = 40.09W	0.09% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 18.40V	V_{MP} = 18.61V	1.14% for V_{MP}
Temperature 75°C	P_{MP} = 44.10W	P_{MP} = 44.15W	0.11% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 20.30V	V_{MP} = 20.51V	1.03% for V_{MP}

3.1.3. Monocrystalline Cells

The comparison between simulation and practical data is shown in Table 3.

It can be noticed that: the average relative error on the maximum power voltage is 0.36% and the average relative error on the maximum power is 0.02%,

Table 3. *Comparison between the developed model and the manufacturer's data (PW500 from PHOTOWATT, monocrystalline).*

Conditions	Data provided by the manufacturer	Model result	Relative error (%)
Temperature 50°C	P_{MP} = 55.00W	P_{MP} = 55.00W	0.00% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 14.60V	V_{MP} = 14.61V	0.06% for V_{MP}
Temperature 25°C	P_{MP} = 70.00W	P_{MP} = 70.00W	0.00% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 16.50V	V_{MP} = 16.50V	0.00% for V_{MP}
Temperature 0°C	P_{MP} = 77.88W	P_{MP} = 77.88W	0.00% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 18.40V	V_{MP} = 18.31V	0.48% for V_{MP}
Temperature 75°C	P_{MP} = 85.75W	P_{MP} = 85.80W	0.05% for P_{MP}
Lighting 1000 W/m^2	V_{MP} = 20.30V	V_{MP} = 20.11V	0.93% for V_{MP}

We present in this study a comparison of the results for the different cell constructors. Table 4 presents the summary of this study.

Table 4. *Average simulation errors on power and voltage for the three technologies.*

Cell type	Amorphous	Polycrystalline	Monocrystalline
Erreur relative moyenne P_{MP}	0.015%	0.16%	0.36%
Erreur relative moyenne V_{MP}	0.36%	1.26%	0.02%

In this part, a general approach on the modeling of photovoltaic modules is presented. The points chosen for the determination of the parameters are the short circuit current point (0, I_{SC}), open circuit voltage point (V_{MP}, *0*), and the maximum power point (V_{MP}, I_{MP}). The data necessary for the evaluation of the modeling method is obtained from the data provided by the manufacturer.

Three types of solar module (amorphous cells, multi-crystalline cells and monocrystalline cells) were tested.

The accuracy of the model is analyzed by comparing the data provided by the manufacturer and the simulation results. The results prove the efficiency of the model (four-parameter model) which takes into account the effect of temperature.

3.2. Characteristics of the Photovoltaic Generator as a Function of Time

3.2.1. Current Characteristic

It is the characteristic of the current when the PV module is not connected to a load under an irradiance of 1000W/m² and a surface temperature of 25°C.

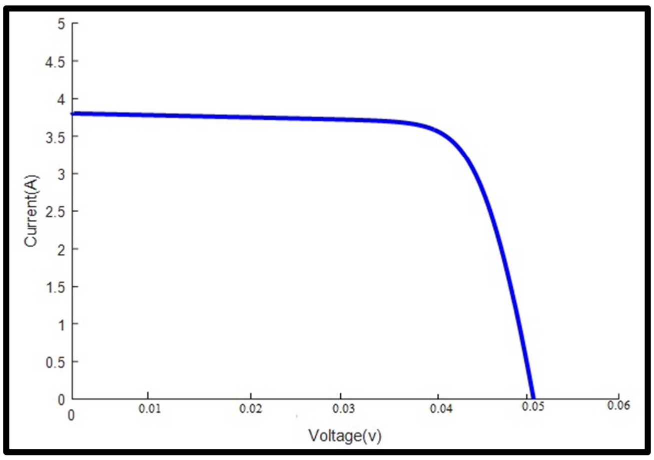

Figure 2. *Current characteristic of the photovoltaic module as a function of time.*

3.2.2. Power Characteristic

This is the output power of the module under nominal operating conditions (G=1000W/m² and T=25°C).

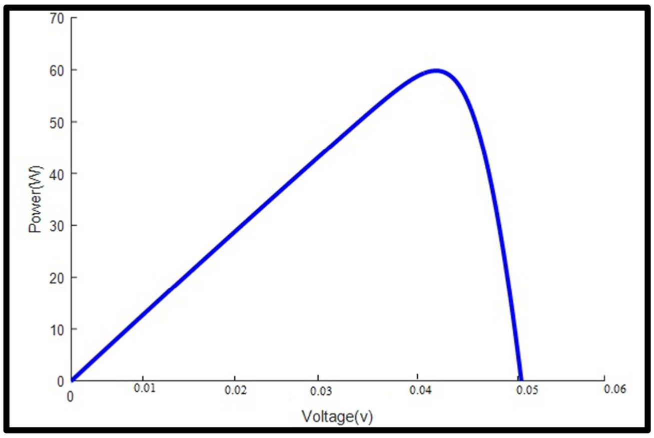

Figure 3. *Photovoltaic module power characteristic.*

The curves obtained show that the profile of the block diagram of Simulink corresponds well to the profile presented in the *M-Files* of Matlab. This allows us to understand that the simulation of the GPV in Simulink works normally.

3.2.3. Connecting a Photovoltaic Generator to a Load

The direct connection between the photovoltaic generator (GPV) and the load makes it possible to determine the operating point of the GPV because it depends on the impedance of the load to which it is connected.

This study was made to observe the influence of weather conditions on the behavior of the PV module. To do this, we inserted a resistive load across the terminals of our module in order to observe the current and the voltage at these terminals.

If the irradiance and the temperature are under the normalized theoretical conditions (G=1000W/m², T=25°C), the current reaches its nominal value after a certain transient time of 3.7 ms which physically corresponds to a response time of 2 ms when looking at 90% of the maximum current (Figure 4).

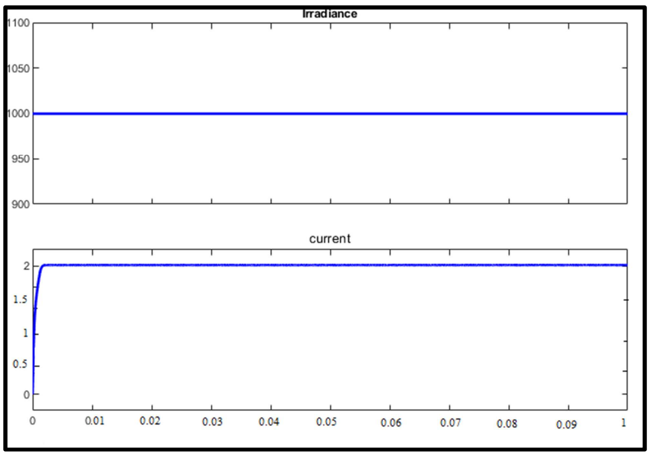

Figure 4. *Characteristic of the current at the output of the GPV at G=1000W/m² and T=25°C.*

Figure 4: Characteristic of the current at the output of the GPV at G=1000W/m² and T=25°C.

We find that when there is no variation, the generator operates normally.

If, on the other hand, the irradiance drops to 400W/m² then rises to 1000W/m² (reflecting a sudden variation in sunshine); we obtain a behavior of the current as a function of the irradiance as presented below:

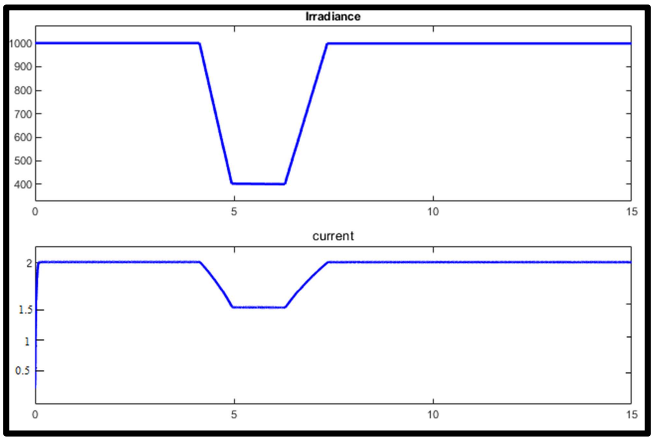

Figure 5. *Characteristic of the current at the output of the GPV when G varies.*

The layout of these two curves makes it possible to directly deduce the response time of our photovoltaic system following any disturbance. On observation, we realize that the disturbance of sunshine is instantly reflected in the current generated by the PV module. This would suggest that the response time of the PV generator is zero; which is theoretically normal because during the simulation, of all the mathematical operations used for the modelling, none takes this parameter into account. On a practical level, this is not entirely accurate. To successfully calculate this response time, the irradiance and current measuring devices must be synchronized. To do this, the data reading step must be of the order of a second.

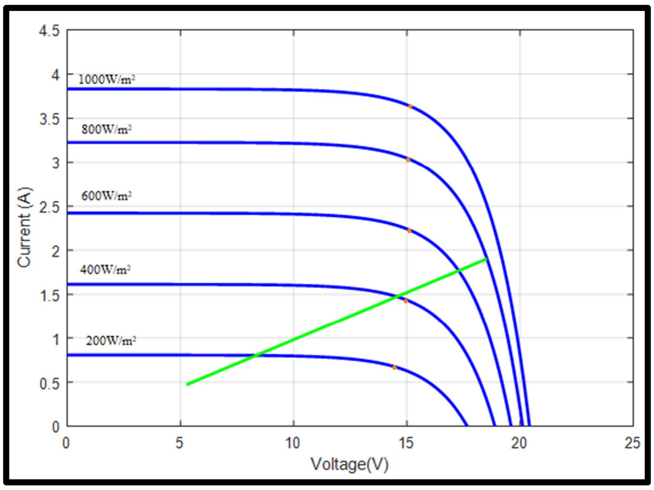

Figure 6. *System current-voltage characteristic (GPV with 10Ω resistive load).*

3.3. Current-Voltage Characteristic of the Operating Point

This characteristic presents the operating point of the system in relation to the maximum power point of the GPV. For each value of the irradiance, our MATLAB program locates the operating point of the system and represents it in green on the two figures.

We find that the operating point of the system is far from the maximum power point.

3.4. Power-Voltage Characteristic

It also shows the operating point of the system in relation to the point of GPV

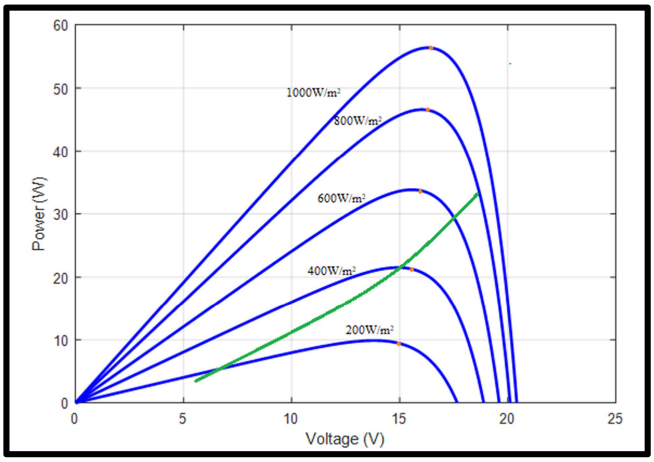

Figure 7. *Power-voltage characteristic of the system.*

We find that the system does not operate at the maximum power point of the GPV. This means that all the power available at the GPV level is not transmitted to the load; hence our system has a poor performance of 33.62%. This efficiency is the ratio between the total energy consumed by the "total energy (simulation)" load and the maximum theoretical energy available at the level of the GPV. The total energy (simulation) is the power consumed by the load multiplied by the time and the total energy (theoretical maximum) is the power available at the GPV multiplied by the time. These values are calculated by the program which made it possible to obtain the current-voltage and power-voltage characteristics of the system.

In this section, it was a question for us to present the different results obtained during the simulation. It therefore emerges at the end of this chapter that the results obtained with the model developed gives results close to the values provided by the manufacturers for both amorphous, monocrystalline and polycrystalline cells with relative errors varying between 0.015 and 1.26%. The response time of the PV generator obtained with this model is estimated at 2 ms during the various simulations the increase in temperature on the surface of the photovoltaic module leads to a decrease in power and the current supplied to the load depends strongly on the intensity of illumination for a given temperature and the nature of the load.

4. Conclusion

In this work, the aim was to study the influence of rapid variations of some meteorological parameters; in particular the sunshine and the temperature at the surface of the cell on the response time of a photovoltaic generator. In the first chapter, the bibliographical study on the photovoltaic generators allowed us to understand the functioning of the photovoltaic cell and the application of the photovoltaic modules in the electricity production. The second chapter presents a modeling of the photovoltaic generator using the four-parameter electrical model and its implementation in the Matlab/simulink environment. The simulation of the system was performed in detail and in several steps in order to clearly illustrate the operation of the photovoltaic generator and its behavior when the two parameters change. The third chapter presents the results obtained after the simulation in the Matlab/Simulink environment. From these results, it can be seen that the developed model gives results close to the values provided by the manufacturers for amorphous, monocrystalline and polycrystalline cells with relative errors varying between 0.015 and 1.26%. The response time of the PV generator obtained with this model is estimated at 2 ms. Through this work, we believe that we have made a contribution to the study of the photovoltaic characteristics of the solar cell in electricity generation. In the future, we plan to design an intelligent circuit that will automatically adjust the maximum power in real time and according to the weather conditions (irradiance, temperature) and load variations.

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