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Simulation and Analysis of I(V) and P(V) Characteristics of a Photovoltaic module under MATLAB/SIMULINK Connected to the Electrical Grid

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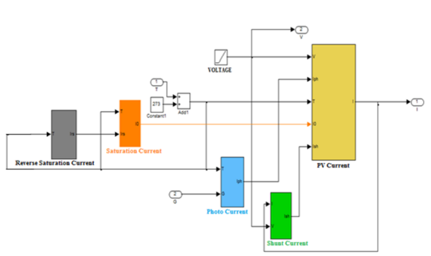
ABSTRACT

The objective of our work is the simulation and analysis of the I(V) and P(V) characteristics of a photovoltaic module under MATLAB/SIMULINK connected to the electrical network. To achieve this goal, we followed the following steps: At the start of work; we performed a simulation of a photovoltaic cell (photovoltaic module). By two methods: by simulation of the mathematical data of the model of a photovoltaic module inspired by the electrical diagram of a photovoltaic cell, by the use of the mathematical equations of: inverse saturation current, saturation current, photonic current, current of the shunt resistance, and the output current to create from each equation a model in MATLAB/SIMULINK, then we collect and connect these models according to the mathematical equation to obtain the final model of the output current of a photovoltaic module, and on the other hand by simulation through the model of the solar cell which exists in the SIMULINK library by checking the data of each box coming from this source. then we showed the Simulation of the BOOST converter with MPPT, and we presented the functional diagram of the PV generator and the BOOST converter with MPPT under MATLAB/SIMULINK, In the same context, we showed the voltage curve at the output of the command MMPT in MATLAB, the current curve at the output of the chopper booster, the curve of the voltage measured at the converter, the curve of the current measured at the converter, the curves of the phase currents of the network and the reference current, and the curve of PV generator power and Pmpp power At the end of the work, we connected this photovoltaic module to an electrical network, to see the impact of our network on the photovoltaic module and vice versa. Finally we explained and interpreted the results obtained according to our points of view.

Keywords: Solar Energy; Photovoltaic Cell; Simulation; MATLAB/SIMULINK; Electrical grid.

Graphical abstract



Block diagram of the photovoltaic module on MATLAB/SIMULINK

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1. Introduction

During the first half of the 20th century, we can distinguish the appearance of several types of renewable energy sources, including: hydroelectric, geothermal, wind, biomass and finally photovoltaic energy. Almost all of its resources come from directly or indirectly from the sun. They are therefore available indefinitely as long as this one shines. The technique most known technology allowing the direct conversion of light into energy and more particularly into electricity is certainly the technique of photovoltaic conversion which consists in convert light directly into electricity [1]. This energy conversion is carried out by means of a so-called photovoltaic cell based on a physical phenomenon called photovoltaic effect which century the photovoltaic made Very little progress. The phenomenon has been demonstrated in systems other than selenium, but without increasing the conversion efficiency, and this until 1954. In this year, Qui marks a great turning point, Carl Fuller, within the laboratories of the Bell company, sought to improve silicon diodes by introducing certain dopants [2,3]. His colleague Gerald Pearson came up with the idea of measuring the current produced under illumination by Fuller diodes . HAS to everyone's surprise, an important current was observed. This was the beginning of a real project of solar cells within the Bell company where a yield of 6% was quickly demonstrated. The year 1954 is also the beginning of thin film cells based on Schottky diodes with the CDS . Because of their high price, the only real, but very important, application for the first solar cells was in the space domain which was the ground of development of photovoltaics until the early 1970s. The year 1958 saw the launch of several satellites equipped with photovoltaic systems [4].

Since the beginning of the 21st century, global energy and environmental issues world have become increasingly important. Solar energy with the advantages of a inexhaustible and clean energy, so it is an effective solution to energy shortages, the environmental pollution and the greenhouse effect [5]. Photovoltaic devices demonstrate that they hold promise for the commercial market as a conversion technology portable renewable energy, which consists of directly converting sunlight into electricity without any heat engine interfering. Today, the photovoltaic market is dominated by silicon solar cells Crystalline (c-Si) in its Multi-crystalline and Mono-crystalline forms [6]. So far, the Crystalline silicon solar cells have achieved efficiency above 25%. Cu (In, Ga) (S,Se)2 (CIGSSe) based cells, one of the layered solar cells most competitive thin films, achieved a conversion efficiency of up to 23.35%. Additionally, perovskite (PVK)-based solar cells have recently emerged, showing Rapid development and opening up new directions in the photovoltaic field [7]. The record efficiency of PVK devices now exceeds 22%. The CIGS material and the Perovskite are semiconductors with an energy gap suitable and a high optical absorption coefficient in the visible range of the spectrum solar. The absorption coefficient of CIGS and Perovskite films is 100 times greater than that of Si in the visible range of the solar spectrum [8]. The improvement in the performance of the solar cell also came through the use of solar cells. solar double-junctions (Tandem), Triple or Multi-junctions which are composed by several absorbers having different gap energies in order to exploit the different regions energies of the solar spectrum [9].

In this work, we try to study and simulate the I(V) and P(V) characteristics of a photovoltaic module through the mathematical model of the data of a photovoltaic module inspired by the electrical diagram of a photovoltaic cell which was shown in the mathematical equation 1, and on the other hand through the solar source that it exists on MATLAB/SIMULINK[10], And at the end of the work we connected this photovoltaic module with an electrical network, to see the impact of our network on the photovoltaic module and vice versa.

1.1. Material Principle of Operation of Photovoltaic Cell

The photovoltaic effect used in solar cells allows direct conversion.

The light energy of the sun's rays into electricity through the production and transport in a semiconductor material of positive and negative electric charges under the effect of light. This material has two parts, one with an excess of electrons and the other with a deficit of electrons, called n-type doped and p-type doped respectively. When the first is brought into contact with the second, the excess electrons in the n material diffuse into the p material. The initially n-doped area becomes positively charged, and the initially p-doped area becomes negatively charged. An electric field is therefore created between them which tends to push back the electrons in the n zone and the holes towards the p zone. A junction (known as p-n) has been formed. By adding metal contacts on the n and p areas, a diode is obtained [11, 12].

The electrons circulate only from the p zone to n and vice versa for the holes. This is due to the use of semiconductor. When the junction is illuminated, the photons of energy equal to or greater than the width of the forbidden band impart their energy to the atoms, each of which passes an electron from the valence band into the conduction band and also leaves a hole capable of move, thus generating an electron-hole pair. If a charge is placed at the terminals of the cell, the electrons of the n zone join the holes of the p zone via the external connection, giving rise to a potential difference: the electric current flows [13].

1.2. Equivalent electrical diagram of Photovoltaic Cell

A photovoltaic cell is based on the physical phenomenon called the photovoltaic effect which consists in establishing an electromotive force when the surface of this cell is exposed to the light. The voltage generated can vary between 0.3 V and 0.7 V depending on the material used and its arrangement as well as the temperature of the cell and the aging of the cell. The energy efficiency performance achieved industrially is 13 to 14% for cells based on mono-crystalline silicon, 11% to 12% with polycrystalline silicon and finally 7 to 8% for amorphous silicon in thin films. The photocell or solar cell is the basic element of a photovoltaic generator [14, 15].

The equivalent diagram is represented by an ideal diode connected in parallel with a current source (fig 1). The series resistances Rs and shunt Rsh model the losses generated by the resistivity of the layers and the presence of leakage currents [16, 17].

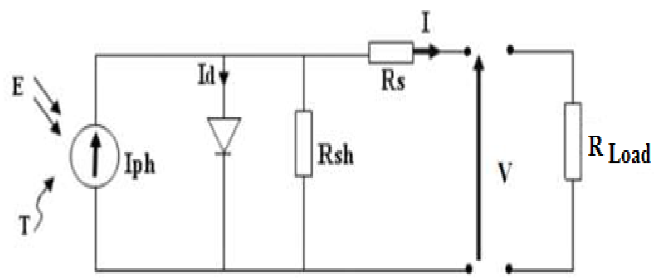

Fig 1. Electrical model of a *PV* cell

This model involves a current generator to model the incident light flux, a diode for the cell polarization phenomena and two resistors (series and shunt) for the losses. This model is said to have five parameters, these parameters are: The photo current (*Iph*), the saturation current (*I0*), the ideality factor of the junction (A), the resistance series (*Rs*) and shunt resistance (*Rsh*). If we neglect the effect of the shunt resistance *Rsh*, by considering it infinite, we find the four-parameter model which is widely used. And if in addition, we neglect the series resistance, we will then find the 3-parameter model.

The choice of the model is made according to the needs of the study [18].

2. Mathematical Modeling of A Module Photovoltaic

According to the electrical diagram of a *PV* cell shown in Fig 1, the current at the output of a photovoltaic module is given by the following relationship [19, 20]:

$$I = I_{ph} - I_0\left[\exp\left(\frac{q.(V + I.R_s)}{n.K.N.T}\right) - 1\right] - I_{sh} \quad (1)$$

Iph: the photonic current
I0: the saturation current of the diode
q: the charge of the electron 1.6 e-19 [eV].
V: The voltage at the output of the photovoltaic module
Rs: The series resistance n: the ideality factor of the diode.
K: Boltzmann constant K=1.38e-23 (J/K)
Ns: number of cells connected in series.
T: The operating temperature (K).
Ish: The current of the shunt resistor (A).
VT: thermal voltage of the diode.
Ki: the cell's short-circuit current at 25C° and 1000W/m2

ISC: the short circuit current
Tn: Nominal temperature (298K)
Vco: The open circuit voltage
Eg0: The semiconductor energy gap
G: Solar irradiation (W/m2).

3. Simulations and Results

Simulating a dynamic system model allows you to gain insight into the behavior of a proposed system design without the tedious process of actually building the system.

In this work, we used an AMD Ryzen 3 2200G processor computer, with 4 GB RAM.

We used MATLAB/SIMULINK 2010.

3.1. Simulation of a photovoltaic module under MATLAB/SIMULINK from mathematical models

Figure 2 shows the diagram of a photovoltaic module on MATLAB/SIMULINK

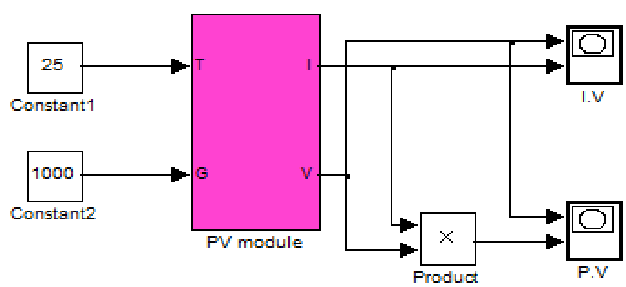

Fig 2. block diagram of a Photovoltaic Module on MATLAB/SIMULINK

If you press PV module the following diagram appears in figure 3.

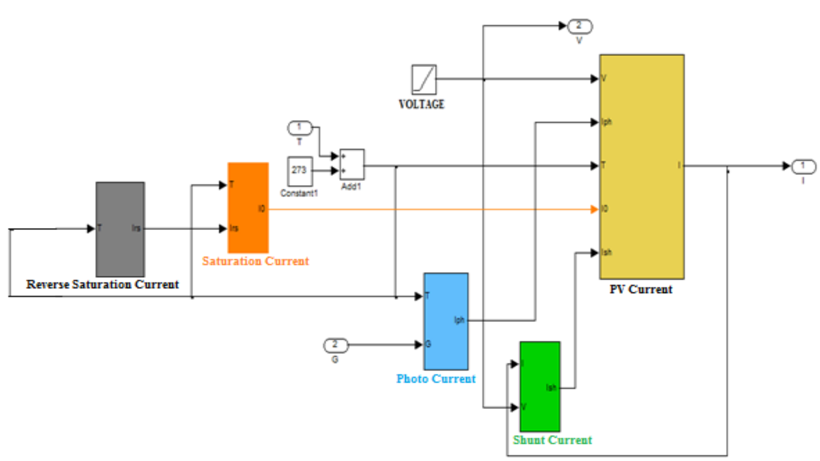

Fig 3. block diagram of the photovoltaic module on MATLAB/SIMULINK

3.1.1. Reverse saturation current

$$I_{rs} = \frac{I_{SC}}{e^{\left(\frac{q.V_{OC}}{n.N_S.K.T}\right)-1}} \qquad (2)$$

Figure 4 is the representation of mathematical equation 2 into SIMULINK

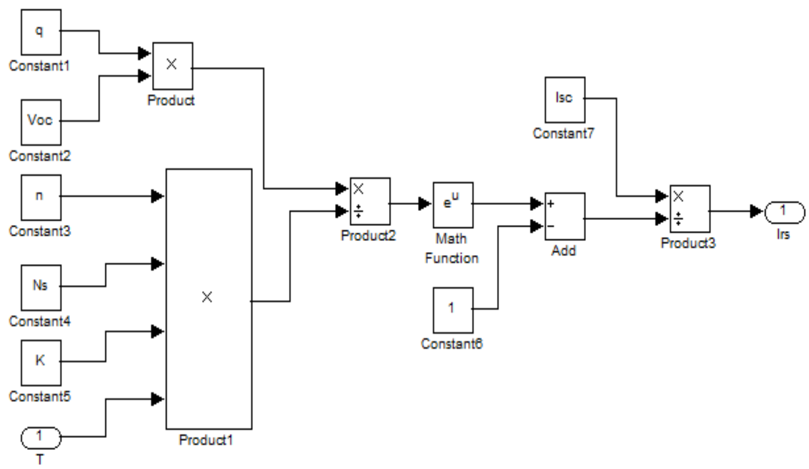

Fig 4. Synoptic diagram of reverse saturation current on MATLAB/SIMULINK

3.1.2. Saturation current I0

$$I_0 = I_{rs}.\left(\frac{T}{T_n}\right)^3 .e^{\frac{q.E_{g0}.\left(\frac{1}{T_n}-\frac{1}{T}\right)}{N.K}} \qquad (3)$$

Figure 5 is of mathematical equation 3 into SIMULINK

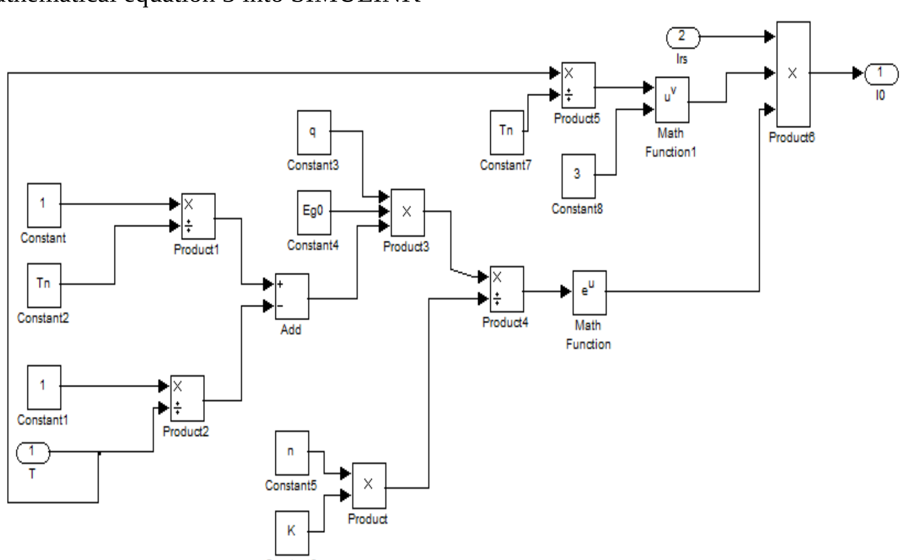

Fig.5. Synoptic diagram of the saturation current on MATLAB/SIMULINK

3.1.3. Photon current Iph

$$I_{ph} = \left[I_{SC} + K_i.(T-298)\right]\frac{G}{1000} \tag{4}$$

Figure 6 is the representation of mathematical equation 4 in SIMULINK.

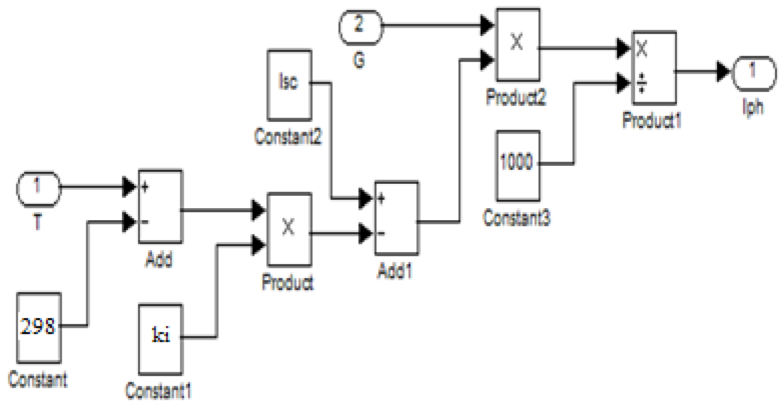

Fig.6. Synoptic diagram of the photonic current on MATLAB/SIMULINK

3.1.4. The current of the shunt resistor

$$I_{sh} = \frac{V + I.R_S}{R_{SH}} \tag{5}$$

Figure 7 is the representation of the mathematical equation 5 on SIMLINK.

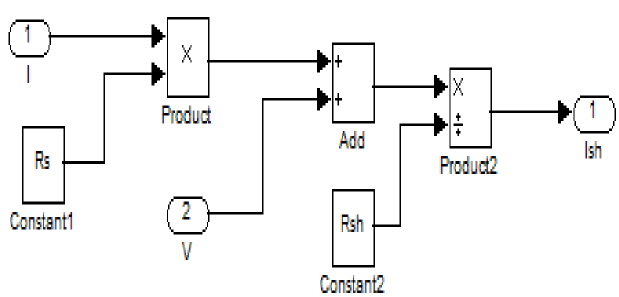

Fig.7. Synoptic diagram of shunt resistor current on MATLAB/SIMULINK

3.1.5. The current at the output

$$I = I_{ph} - I_0\left[\exp\left(\frac{q.(V + I.R_S)}{n.K.N.T}\right) - 1\right] - I_{Sh} \tag{6}$$

Figure 8 is the representation of the mathematical equation 6 on SIMLINK.

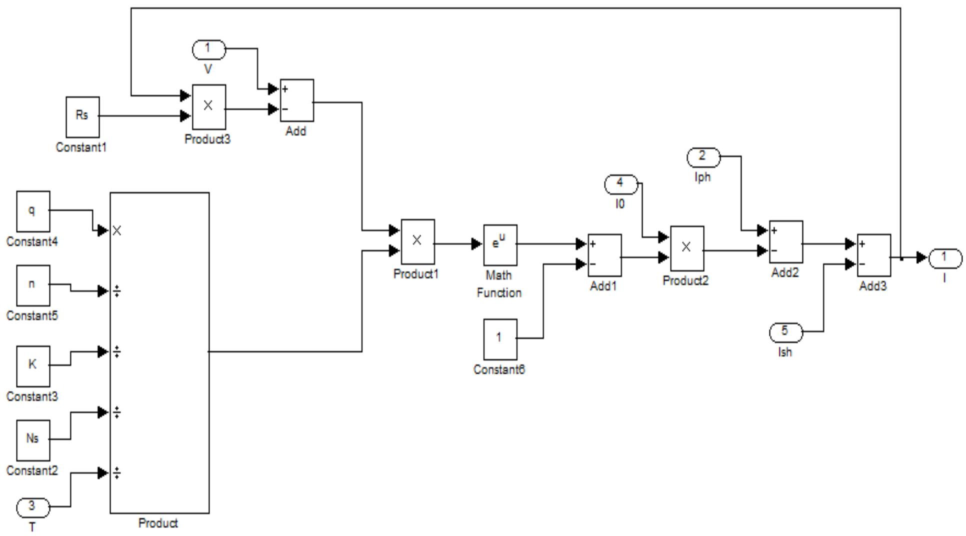

Fig.8.Summary diagram of output current on MATLAB/SIMULINK

3.1.6. I(V) and P(V) characteristics of a photovoltaic module under MATLAB/SIMULINK

The simulation of a PV generator under standard conditions (E=1000 w/m² and T=25°), gave the curves presented in (fig 9 and fig 10).

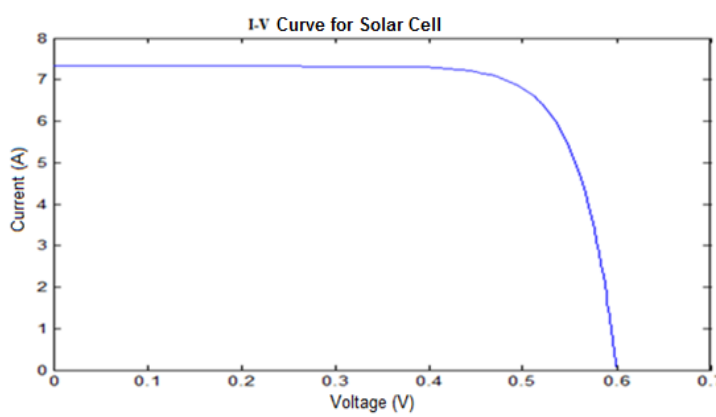

Fig.9. *I(V)* characteristics of a photovoltaic cell

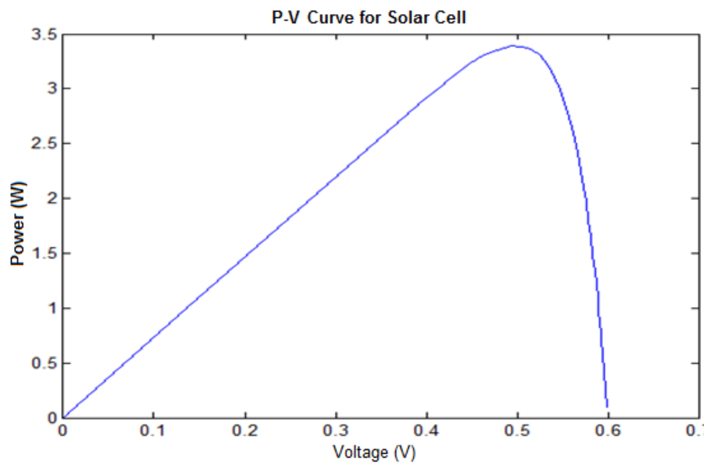

Fig.10. *P(V)* characteristics of a photovoltaic cell

The characteristic of a PV cell (or of a PV generator) is directly dependent on the solar irradiation and the temperature. The variations of current and power as a function of voltage for different levels of illumination at a constant temperature of 25°C, fig 11 and fig 12, show clearly the existence of maxima on the power curves corresponding to the Maximum Power Points Pmax.

When the irradiation varies for a given temperature, the current short-circuit voltage Isc varies proportionally to the irradiation. At the same time, the open circuit voltage Vco (no load) varies very little.

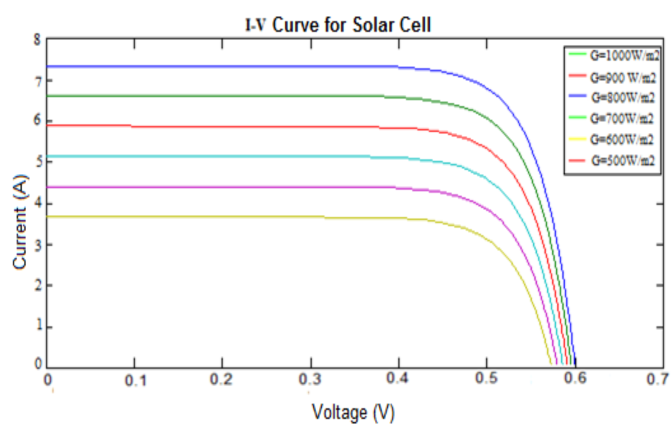

Fig 11. *I(V)* characteristics of a photovoltaic cell for different levels of solar irradiation (T=25°C)

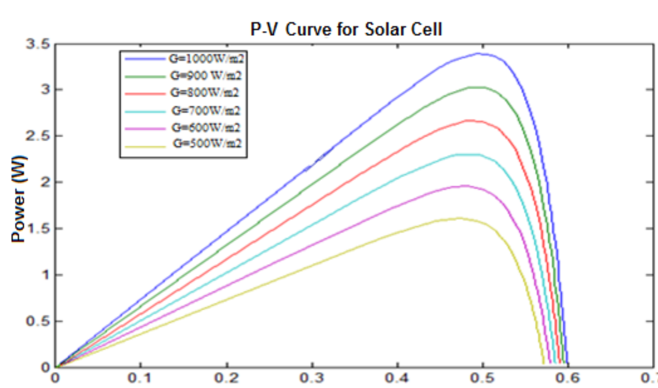

Fig 12. *P(V)* characteristics of a photovoltaic cell for different levels of solar irradiation (T25°C)

3.2. Simulation of a photovoltaic module under MATLAB/SIMULINK

From the SIMULINK Library, the figure 13 represents the block diagram of a photovoltaic cell existing on the SIMULINK library

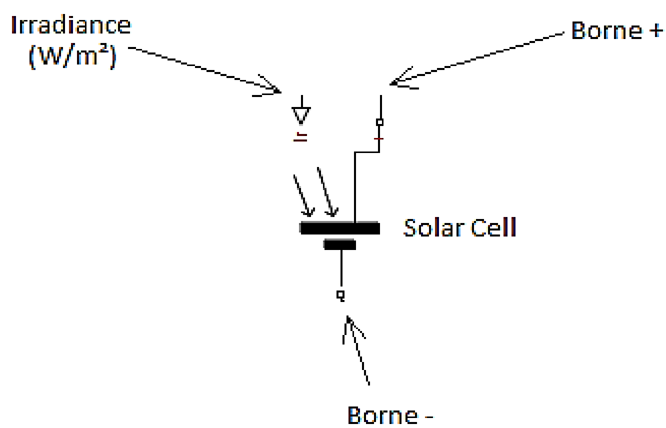

Fig 13. SIMULINK block representing the photovoltaic cell.

The following figure 14 represents the block diagram of the PV cell in MATLAB/SIMULINK:

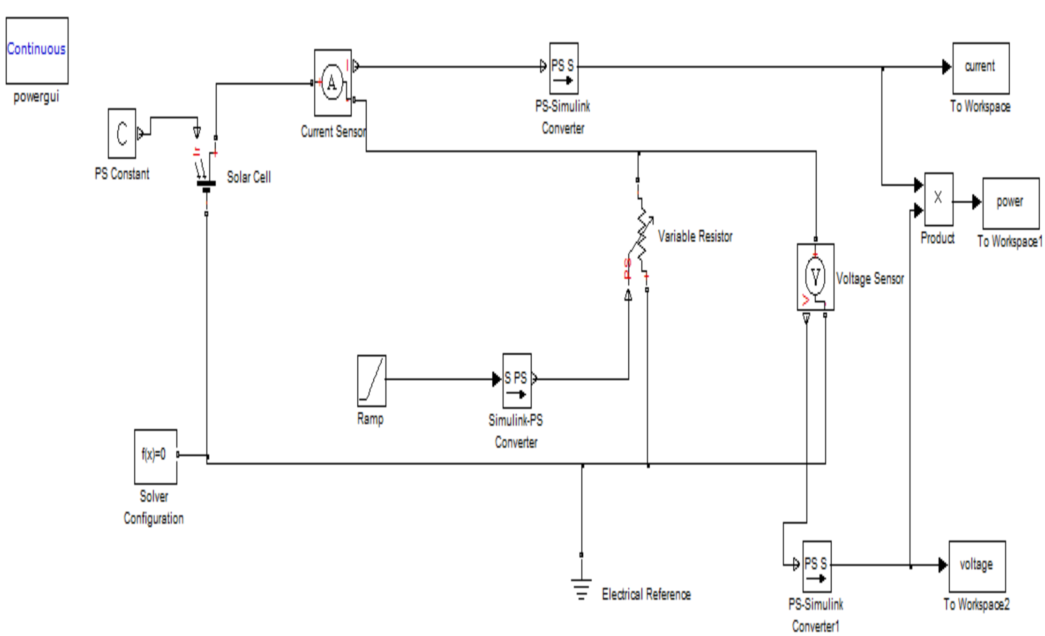

Fig 14. Block diagram of the PV cell in MATLAB-SIMULINK

3.2.1. I(V) and P(V) characteristics of a photovoltaic module under MATLAB/SIMULINK

Fig 15 and fig 16 represent the current-voltage I(V) and power-voltage P(V) characteristics of a photovoltaic cell using the model under standard conditions (T=25C°, and G=1000W/m2).

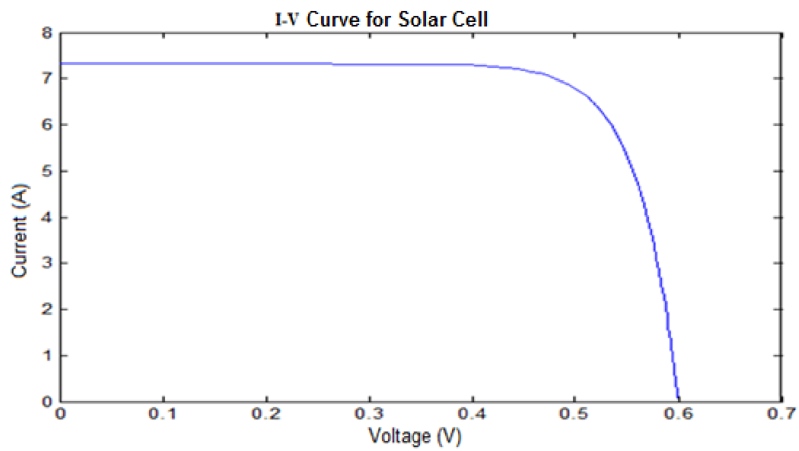

Fig 15. *I(V)* characteristics of a MATLAB/SIMULINK

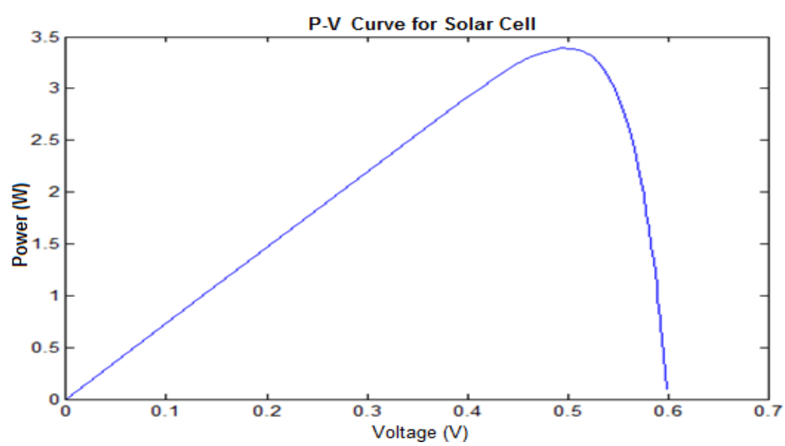

Fig 16. *P(V)* characteristics of a photovoltaic cell

Temperature is a very important parameter in the behavior of solar cells. The temperature also has an influence on the characteristic of a PV generator. fig 17 and fig 18 show the variation of the characteristics of a PV cell as a function of the temperature at a given solar irradiation. The solar irradiation here is set at 1000W/m2.

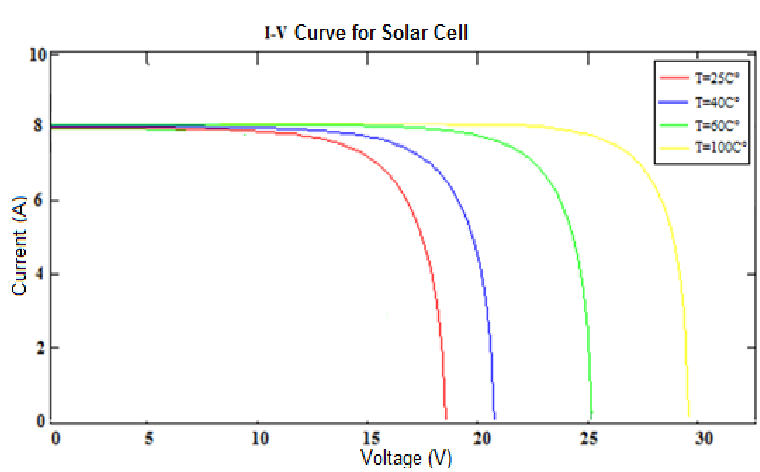

Fig.17. I(V) characteristics of a photovoltaic cell for different temperatures (G=1000W/m2).

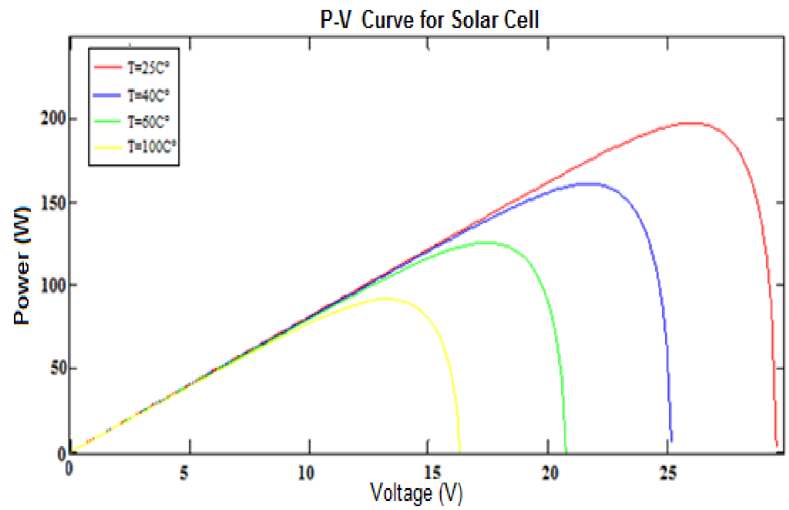

Fig.18. P(V) characteristics of a photovoltaic cell for different temperatures (G=1000W/m²).

The variations of current and power as a function of voltage for different levels of solar irradiation at a temperature kept constant at 25°C, fig 19 and fig 20, show clearly the existence of maxima on the power curves corresponding to the Maximum Power Points Pmax. When the solar irradiation varies for a given temperature, the current of short-circuit Isc varies proportionally to the irradiation. At the same time, the open circuit voltage Vco (no load) varies very little.

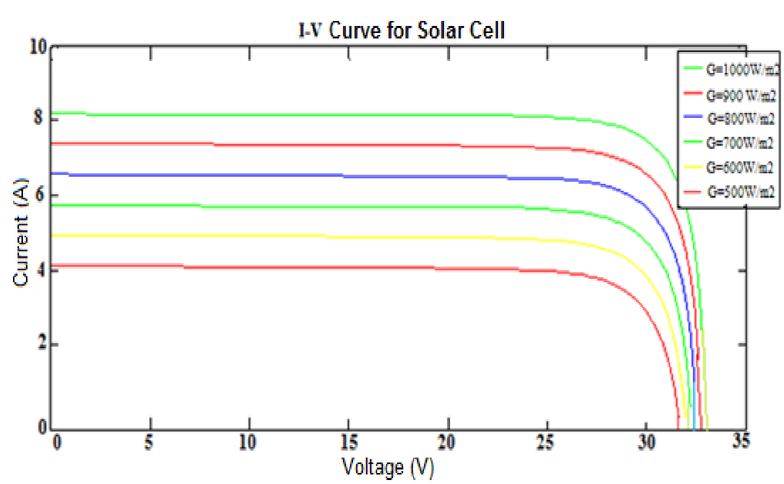

Fig 19. *I(V)* characteristics of a photovoltaic cell for different levels of solar irradiation (T=25C°).

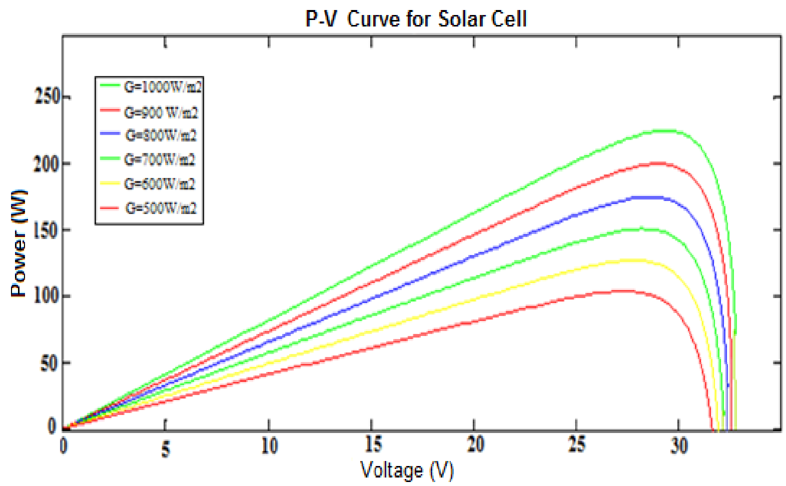

Fig 20. *P(V)* characteristics of a photovoltaic cell for different levels of solar irradiation (T=25°C).

3.3. Simulation of the BOOST converter with MPPT

Figure 21 represents Block diagram of the PV generator and BOOST converter with MPPT

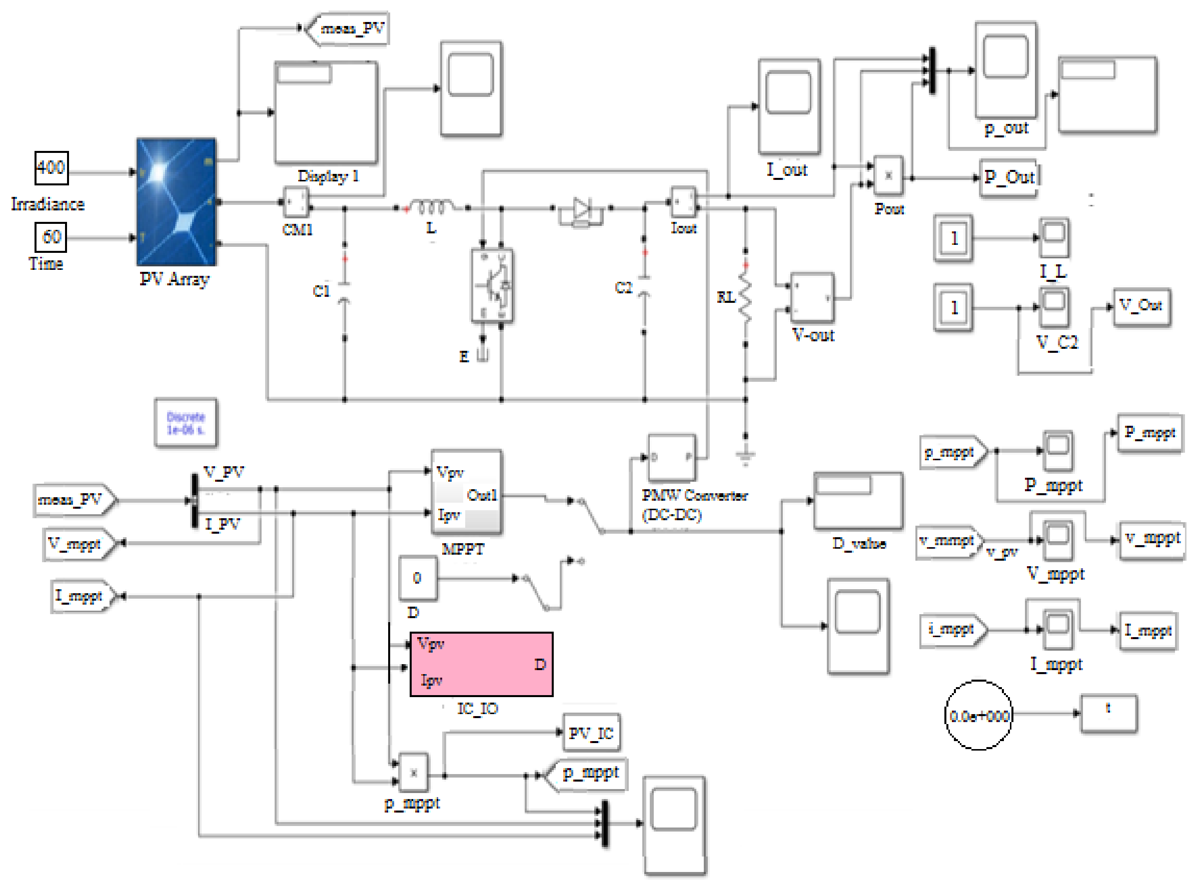

Fig 21 . Simulink model for (PVG, boost converter and MPPT)

The following figure 22 represents the voltage at the output of the MPPT command in MATLAB

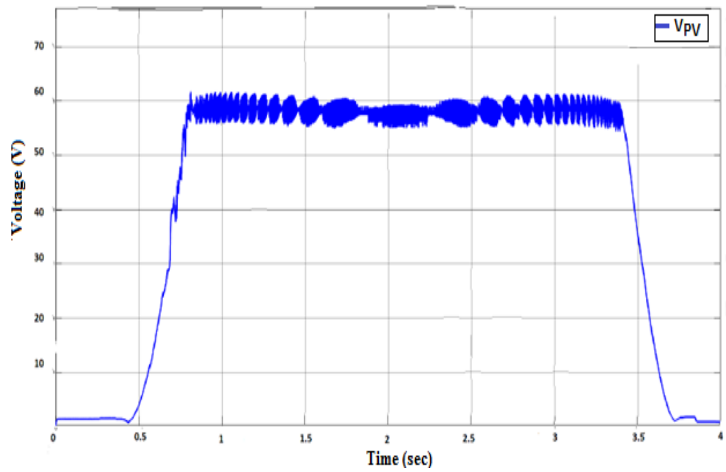

Fig 22 . Voltage curve at the output of the MPPT command in MATLAB

The figure 23 represents the current at the output of the booster chopper

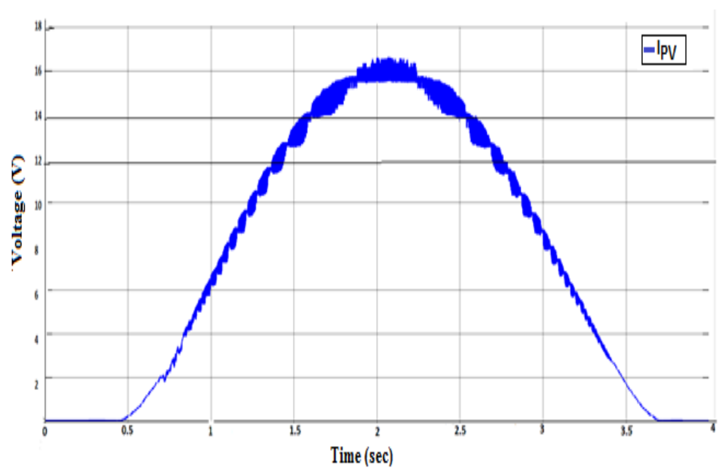

Fig 23. Current curve at the output of the booster chopper

The figure 24 represents the voltage measured at the converter

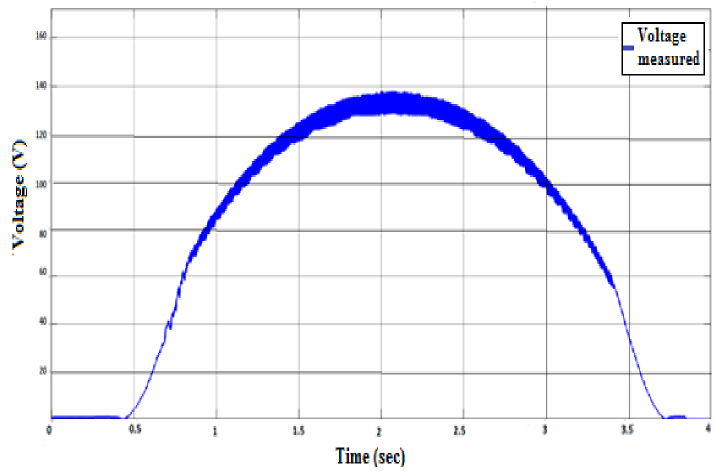

Fig 24 .Curve of the voltage measured at the converter

The figure 25 represents the current measured at the converter

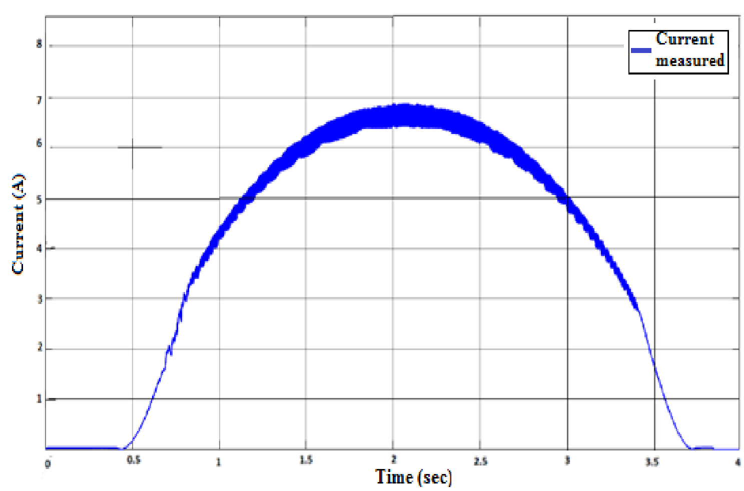

Fig.25. Curve of the current measured at the converter

These figures represent the voltage, current and power generated by the photovoltaic generator, as well as the voltage, current and power at the output of the photovoltaic system. These results show that the booster chopper and the MPPT control by the P&O method perform their roles correctly. The booster chopper provides a voltage at its output higher than that provided by the photovoltaic generator. And the *MPPT* control adapts the *PV* generator to the load: transfer of the maximum power supplied by the *PV* generator.

3.4. Modeling of the PV system Connected to the electrical Grid

Figure 26 shows the global grid connection scheme. We used the block diagram assembly of this figure for the control and injection of power into the electrical grid and searched for the maximum power point. This diagram contains the different blocks:

- PV generator block diagram
- Booster Chopper block diagram
- Mppt control block diagram

- Inverter block diagram
- Our grid block diagram

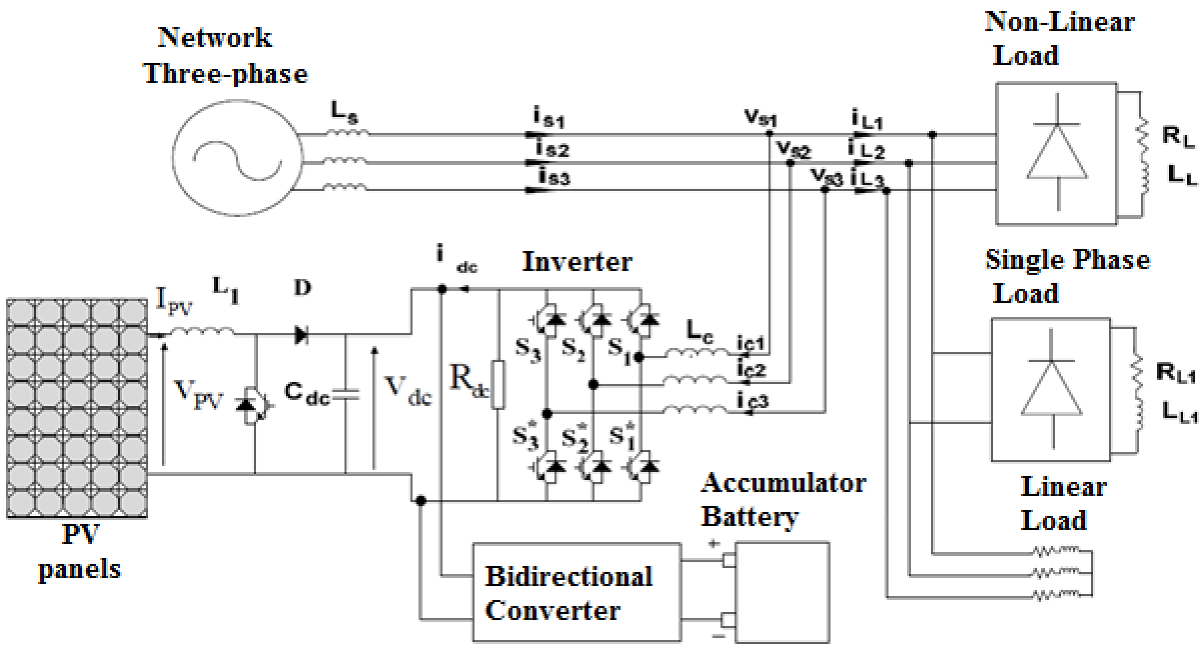

Fig 26. Overall diagram of the grid-connected PV system

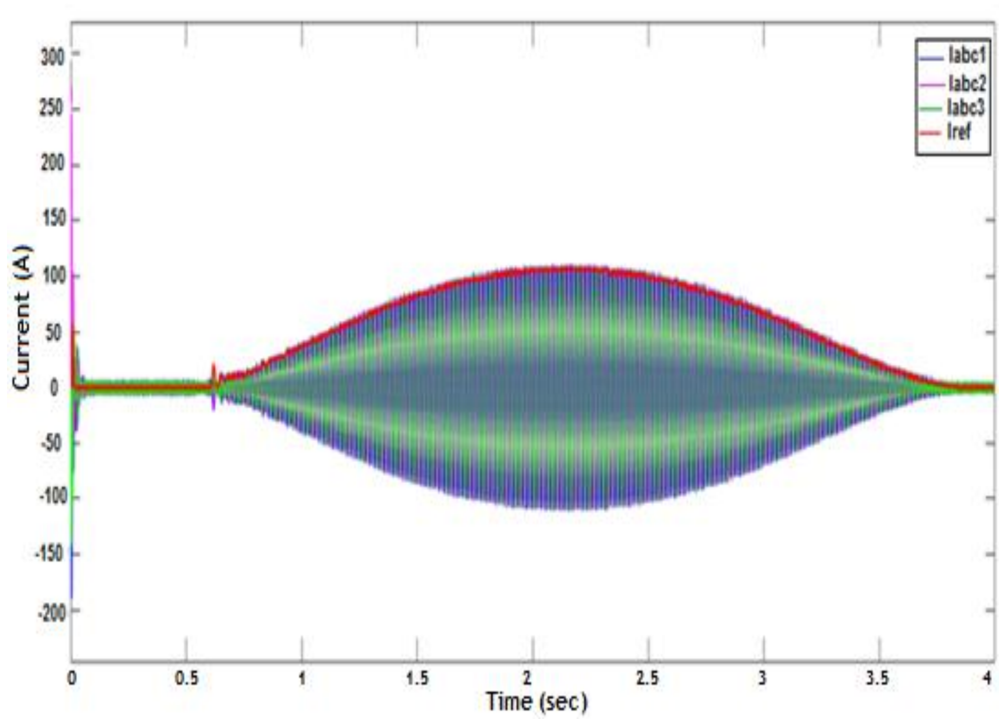

Fig 27 .Curves of network phase currents and reference current

Figure 28 shows the PV generator power and Pmpp power curve

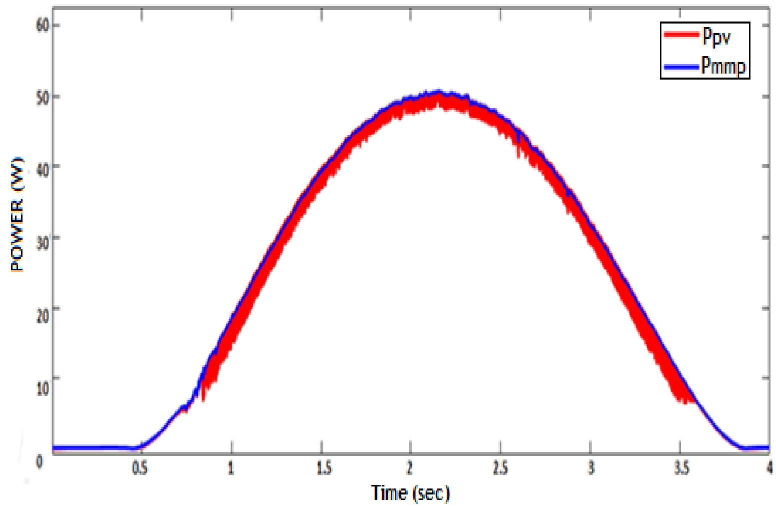

Fig 28.Curve of the PV generator power, and the power Pmpp

From figure 27, we notice that the currents of the phases in our network are identical with the reference current. Following figure 28, we notice that the power delivered by the photovoltaic generator is similar with the power delivered by PPM.

4. Conclusion

In this work, we presented fundamental electrical characteristics of a photovoltaic cell (photovoltaic module). By two methods: by simulation of the model mathematical data of a photovoltaic module inspired by the electrical diagram of a photovoltaic cell, and on the other hand by simulation through the model of the solar cell that exists in the SIMULINK library.

We have seen that the *PV* cell has a nonlinear *I(V)* characteristic, has a maximum power point *(PPM)* characterized by current (Imax) and voltage (*Vmax*), and can be modeled by a circuit single electric. We have presented the influence of the various external parameters on this characteristic. The short-circuit current evolves mainly with the illumination and the voltage vacuum with temperature.

If the temperature increases at constant irradiation, the no-load voltage *Vco* decreases with the temperature. The higher the temperature, the lower *Vco* and the short-circuit current Isc increases with the temperature. This increase is much less significant than the drop in voltage. The influence of temperature on *Isc* can be neglected in most cases.

Temperature and solar irradiation are therefore the two main parameters that will modify the characteristics of a PV generator. These two parameters must therefore be studied carefully when setting up a PV installation.

Our objective in this study is the simulation and analysis of a photovoltaic system and its connection to the electrical network.

Funding Support

This research received no external funding.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

Not applicable.

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