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Design and Control of an Autonomous PV System with Battery Storage and Single Phase Inverter using the Smart Control Followed by PI Correctors

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Abstract*: The autonomous photovoltaic system requires a battery for storage of energy, for consumption during the night and days with low irradiation. This article presents the design and control of the autonomous PV system with a storage battery and a single-phase inverter. The SEPIC converter is used to adapt the output voltage of the PV panel to the battery charging voltage, this converter is controlled by the intelligent MPPT control followed by PI controllers to extract the maximum power of the GPV and manage the charge and discharging loop the battery. Subsequently, a BOOST converter has been associated with the system to adapt the output voltage of the battery to the load. The modelling of the state space is done to determine the transfer function of the converters (SEPIC and BOOST). The single-phase inverter is used to supply alternative loads. The values of the PI correctors (Kp and Ki) are obtained using the method of Ziegler Nichols. Finally, we simulated and analysed the performance of a 250W stand-alone photovoltaic power system on MATLAB-Simulink.

Keywords: Autonomous photovoltaic system, battery storage, SEPIC and BOOST converter, Single phase inverter, PI controller, intelligent control.

I. INTRODUCTION

With the depletion of fossil fuel reserves, economic crises due to soaring oil prices, accidents at nuclear power plants such as Three Mile Island (USA, 1979) and Chernobyl (USSR, 1986), aswell as Fukushima (Japan 2011) public interest in renewable energies continues to grow. Of the various sources of renewable energy, photovoltaic occupies a prominent place [1]. In stand-alone photovoltaic systems, batteries are widely used to power loads in the absence of sunshine or in the event of a failure of the solar energy system. These batteries are sensitive to overload, deep discharge and temperature and current drift. It is then necessary to associate them with a regulator to ensure their protection. The importance of a charge controller in an autonomous photovoltaic system is obvious. However, it must be well designed to meet the requirements of cost, simplicity, and reliability [1] [3]. In this work we study an autonomous photovoltaic system with a battery charger for energy storage, controlled by an MPPT command with two PI correctors, one intended for the control of the state of charge battery discharge and the other to adapt the output voltage of the battery to the load. The article is structured as follows: firstly we present the operation of the autonomous photovoltaic system, then the modeling of the state space of the converters (SEPIC and BOOST), after the single-phase inverter is used to supply alternative loads and the method of Ziegler and Nichols is presented to determine the values of PI correctors, later we present the system control algorithm and finally the results and the discussion.

II. MATERIALS AND METHODS

A. Autonomous PV system

An autonomous photovoltaic system is one that produces electricity through the sun, but operates independently of the electricity grid. In the majority of cases, this system is used in isolated sites where it would be much too expensive to connect the house or the room that you want to supply with electricity. The major difference with a standard photovoltaic installation (connected to the grid) is the presence of batteries. An autonomous photovoltaic system must be able to provide energy, even when there is no more sun (at night or in bad weather). It is therefore necessary that a part of the daily production of the photovoltaic modules is stored. Below is the synoptic diagram of our autonomous photovoltaic system that consists of a GPV with a SEPIC type converter to charge the battery and a BOOST converter to power our load and the single-phase inverter is used to supply alternative loads [3] [9].

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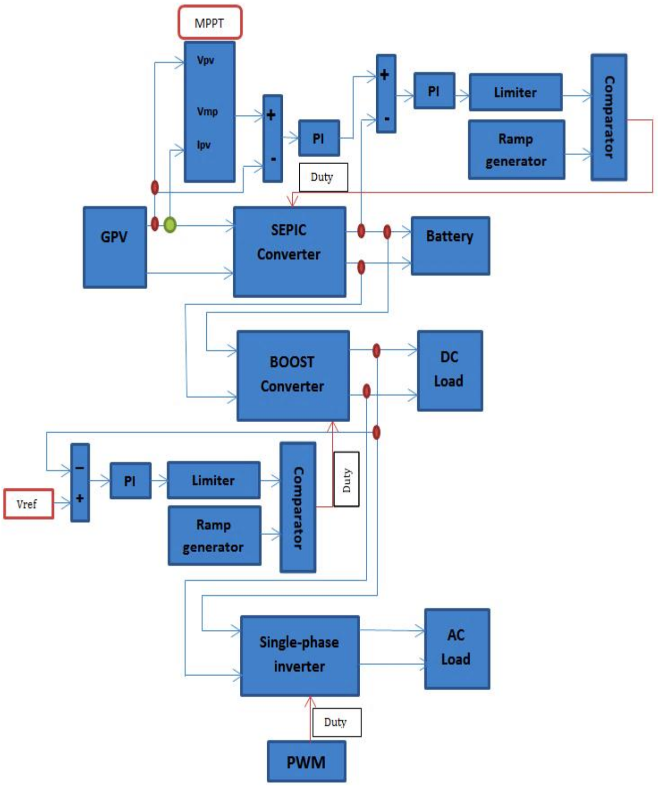

Fig.1. Synoptic diagram of the photovoltaic

For this study, we used a PV ASW-250P, with the following parameters:

Table- I: Characteristic of the PV module

American Solar Wholesale ASW-250P	*Value*
Maximum power(W)	249.92
Open circuit Volatge Voc(V)	43,22
Short-Ciruit curant Isc (A)	7.76
Voltage at maximum power point Vmp(V)	35.2
Current at maximum power point Imp(A)	7.1
Shunt resistance Rsh(ohms)	111.87
Series resistance Rsh(ohms)	0.42

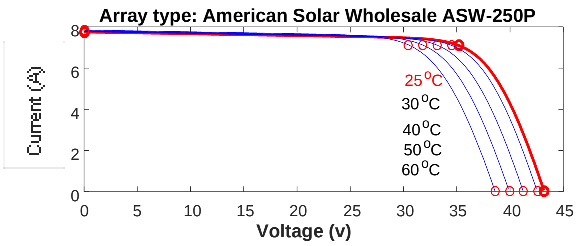

Fig.2. Ipv=f(Vpv) for influence of temperature

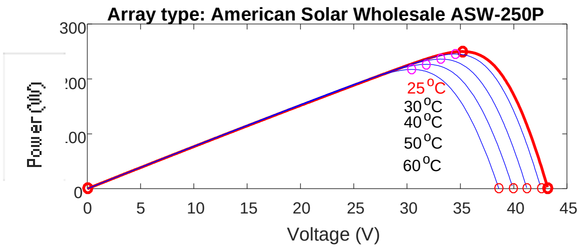

Fig.3. Ppv=f(Vpv) for influence of temperature

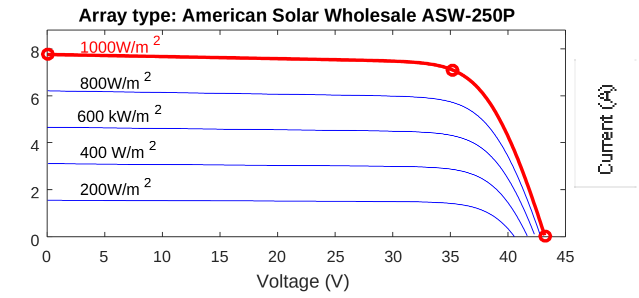

Fig.4. Ipv=f(Vpv) for influence of Illumination

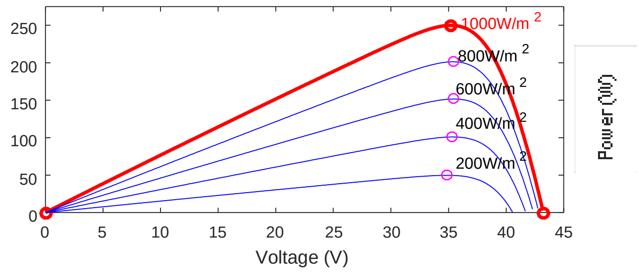

Fig.5. Ppv=f(Vpv) for influence of Illumination

B. Modeling the converter

a. SEPIC converter

A SEPIC is a type of DC-DC converter allowing the electrical potential (voltage) at its output to be lower, greater or equal to that at its input. The use of the SEPIC converter (which can play the role of a boost converter if α> 0.5 or step down if α <0.5) is explained by the fact that the voltage delivered by the panel is greater than the voltage of the battery which is 24 V and has the advantage of having a non-inverted output [3].

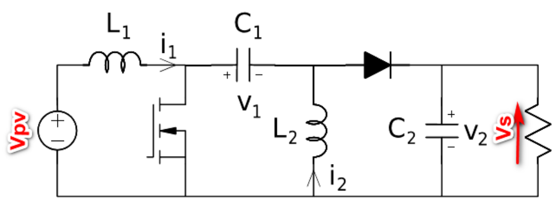

Fig.6. SEPIC converter circuit

In CCM mode, the duty cycle for SEPIC converter is given by [2]:

$$\alpha = \frac{Vs + V_d}{Vs + Vpv + V_d} \text{wiht} \quad 0 < \alpha < 1 \qquad (1)$$

The PI regulator is used to monitor the state of charge-discharge of the battery and to size these parameters Ziegler and Nichols have proposed a method that requires the recording of the index response in open loop, just record the answer index of the process alone (i.e. without the regulator), then draw the tangent to the point of inflection of the curve. To do this the determination of the transfer function of the converter is mandatory. To determine the transfer function of the SEPIC converter we used the space model. In ON state we found equation (2) by using the deferential equation model [2]:

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$$\begin{bmatrix} \frac{dL_{L1}}{dt} \\ \frac{dL_{L2}}{dt} \\ \frac{dV_{cs}}{dt} \\ \frac{dV_{C(OUT)}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & 0 \\ 0 & -\frac{1}{C_1} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{RC_{OUT}} \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cs} \\ V_{COUT} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_{IN}] \tag{2}$$

In OFF state we found equation (3) by using the deferential equation model:

$$\begin{bmatrix} \frac{dL_{L1}}{dt} \\ \frac{dL_{L2}}{dt} \\ \frac{dV_{cs}}{dt} \\ \frac{dV_{C(OUT)}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & -\frac{1}{L_1} \\ 0 & 0 & 0 & -\frac{1}{L_2} \\ \frac{1}{C_{cs}} & 0 & 0 & 0 \\ \frac{1}{C_{OUT}} & \frac{1}{C_{OUT}} & 0 & -\frac{1}{RC_{OUT}} \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cs} \\ V_{COUT} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_{IN}] \tag{3}$$

By using the Laplace transform, the transfer function is written as follows [11]:

$$\frac{Y(s)}{U(s)} = C(Sl - A)^{-1}B \tag{4}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{A_1S^3 + A_2S^2 + A_3S + A_4}{A_5S^4 + A_6S^3 + A_7S^2 + A_8S + A_9} \tag{5}$$

Avec: (6)

$A_1 = L_1\, C_S L_2 \alpha$
$A_2 = L_1\, C_S R \alpha^2$
$A_3 = -\alpha^2 L_1$
$A_4 = \alpha^2 R$
$A_5 = (1-\alpha)^2 L_1\, C_S L_2 C_{OUT} R$
$A_6 = (1-\alpha)^2 L_1\, C_S L_2$
$A_7 = (1-\alpha)^2 R(L_1 C_S (1-\alpha)^2 + L_1 C_{OUT}(1-\alpha)^2 + C_S L_2 (1-\alpha)^2 + L_1\, C_{OUT}\alpha^2)$
$A_8 = (1-\alpha)^2 (L_2(1-\alpha)^2 + L_1\alpha^2)$
$A_9 = (1-\alpha)^4 R$

The values of the inductances are calculated as follows:

$$L_1 = L_2 = \frac{V_{pv}}{\Delta I_L \times f_{sw}} \tag{7}$$

The values of the output and coupling capacitors are calculated as follows:

$$C_s \geq \frac{I_S}{V_{Cs\ ripple} \times 0.5 \times f_{sw}} \times \alpha \tag{8}$$

$$C_c = \frac{i_s \alpha}{\Delta u_{Cc} \times f_{sw}} \tag{9}$$

The following table summarizes the values of the SEPIC converter parameters.

Table- II: Dimensioning of the SEPIC converter

SEPIC converter Parameters	*Value*
Cyclic duty α	0,41
Cutting frequency	100KHz
Value of inductance (L1 et L2)	200µH
Output capacitor	1000µF
Coupling capacitor	47µF
Input voltage Vpv	35.2V
Output voltage Vout	24V
Power Ppv	250W

The following figure illustrates the open-loop step response of the SEPIC converter.

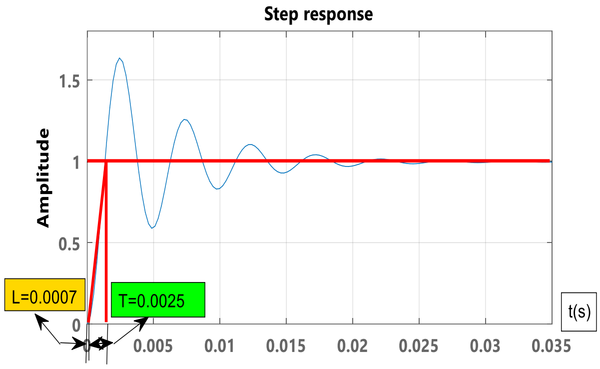

Fig.7 . Open loop index response of the SEPIC converter SEPIC

Using the Ziegler and Nichols settings, we obtain the values of our PI controller [5] [6]:

$$K_p = \frac{0.9T}{L} = 3.21 \tag{10}$$

$$T_i = \frac{L}{0.3} = 0.0023\ s \tag{11}$$

With:
-Delay time L = 0.0007s
-Time constant T = 0.0025s

b. BOOST converter

At Boost converter the average output voltage V_2 is higher than that of the input V_1. The BOOST converter is used to adapt the output voltage of the battery to the load [4].

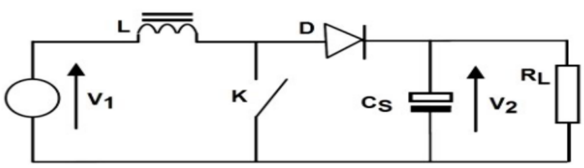

Fig.8. Boost converter circuit

In CCM mode, the duty cycle is given by:

$$\alpha = \frac{V_1 - V_2}{V_2} \text{ avec } 0 < \alpha < 1 \tag{12}$$

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To adapt the output voltage of the battery to the load the PI regulator is used, these parameters are obtained by the use of Ziegler and Nichols method. To make this study the determination of the transfer function of the converter is mandatory. Following the same procedure of SEPIC converter we have [5]:

If the transistor is in the ON state:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 0\\ 0 & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V_{pv} \quad (13)$$

If the transistor is in the OFF state:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V_{pv} \quad (14)$$

By application of the Laplace transform [11], the transfer function is written as:

$$\frac{Vs}{Vpv} = \frac{\alpha}{RC(1-\alpha)^2} \times \frac{\frac{R(1-\alpha)^2}{L} - S}{S^2 + \frac{S}{RC} + \frac{(1-\alpha)^2}{LC}} \quad (15)$$

The value of the inductance is calculated as follows:

$$L = \frac{\alpha \times V_{bat}}{f_{sw} \times \Delta I} \quad (16)$$

We calculate the value of Cs (Output capacitor) by using the following equation:

$$C_s = \frac{I_s \alpha}{f_{sw} \Delta V_{Cs}} \quad (17)$$

The following table summarizes the values of the BOOST converter parameters using the model (17).

Table- III: Dimensioning of the BOOST converter

BOOST converter Parameters	*Value*
Cyclic duty α	0,5
Cutting frequency	100KHz
Value of inductance L1	200μH
Output capacitor	47μF
Input voltage Vbat	24V
Output voltage Vs	48V
Charge R	10Ω

The following figure illustrates the open-loop step response of the BOOST converter.

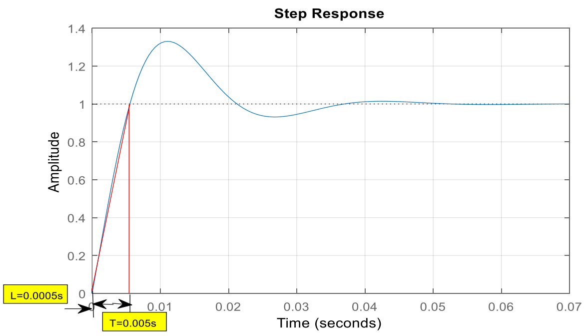

Fig. 9. Open loop step response of the BOOST converter

Using the Ziegler and Nichols settings, we obtain the values of our PI controller [5] [6]:

$$K_p = \frac{0.9T}{L} = 9 \quad (18)$$

$$T_i = \frac{L}{0.3} = 0.0016\ s \quad (19)$$

With:
-Delay time L = 0.0005s
-Time constant T = 0.005s

C. Dimensioning battery voltage

We recall that a battery consists of several electrochemical conversion elements. Each element is considered as a voltage generator of 2V. By stacking these elements, one obtains batteries of 6V, 12V, 24V or 48V.

In order to determine the appropriate voltage of the battery, it is appropriate to be placed in the most unfavorable configuration, that is to say when the batteries completely power the electrical equipment (without any contribution of the photovoltaic field) [3] [14].

The mathematical formula for determining the battery voltage is shown below:

$$V_{bat} = \sqrt{\frac{\rho \times 2 \times L \times P}{S \times \varepsilon}} \quad (20)$$

With:

- **ρ:** resistivity of the conductive material under operating temperature conditions, expressed in Ω.mm² / m. We consider that ρ = 1.25 × ρ0 where ρ0 is the resistivity of the conductor at 20 ° C.
- **L:** Length of the cables connecting the battery to the distribution board, expressed in m. The factor 2 makes it possible to take into account the distances to and from the cable.
- **P:** is the electrical power, expressed in W.
- **S:** Cable cross-section between the battery and the distribution board, in mm².
- **ε:** Voltage drop tolerated between the battery and the distribution board

In our case we used a voltage battery:

$$V_{bat} = 24V \quad (21)$$

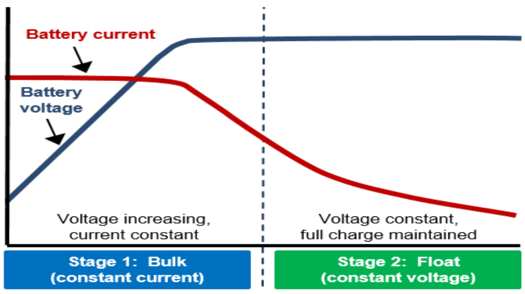

Fig.10. Battery charge profile

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a. Calculation of the nominal capacity of the battery

The nominal capacity of the battery, noted CN (C10), makes it possible to quantify the autonomy of the battery vis-à-vis the electrical consumption of the equipment.

$$C_{10} = \frac{\text{Autonomie} \times \text{Energie journaliére}}{1 - \alpha_f} \quad (22)$$

With:

- α_f: Desired end state of charge

b. Determination of charging time

The charging time T is the time required for recharging a battery can be estimated by calculation

$$T = \frac{Q}{I} \quad (23)$$

- Q : the maximum electric charge of a battery announced in amperes-hours (Ah)
- I : The rated load current I

For our case we use

$$T = \frac{7}{1} = 7h \quad (24)$$

D. Single phase inverter

Inverter is defined as an Electrical device that converts a continuous energy into an alternative energy .

The purpose of this study is to design a following characteristic inverter:

Table- IV: inverter characteristic

Inverter Parameters	*Value*
Power	1KVA
Input voltage	48 VDC
Output voltage	230 VAC
Frequency	50 Hz

The circuit diagram of the inverter used is as follows, this circuit is for supplying the alternating loads

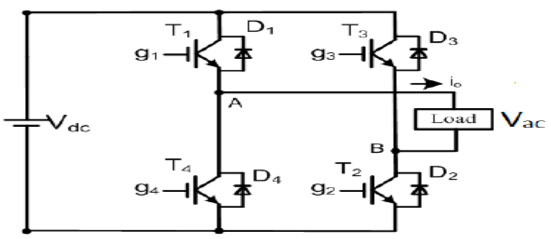

Fig.11. Circuit diagram of the single phase inverter

III. SMART CONTROL

A. Maximum power point tracking

A maximum power point tracking (MPPT abbreviation), MPP regulator or MPP tracker is a principle to follow, as its name suggests, the maximum power point of a generator non-linear electric. MPPT systems are used for photovoltaic generators to extract the maximum power of the panel regardless of temperature or irradiation variation [7] [8].

B. Algorithm of the PandO command

The diagram below present the PandO (The perturb and observe control) algorithm used to extract the maximum power generated by the PV panel, regardless of temperature variation or irradiation [9].

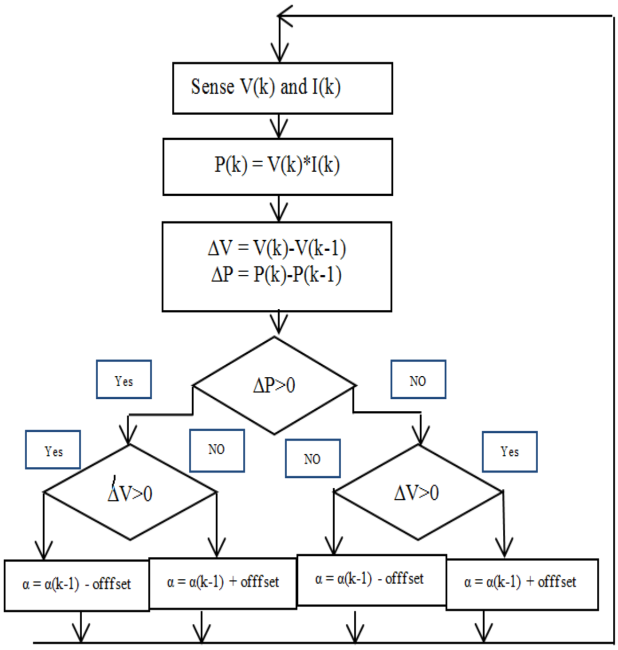

Fig.12. PandO algorithm

C. PI controller

In this way the systems are intended to ensure equality (or at least the smallest error) between the setpoint and the output.

The goal of using the PI controllers is to monitor the state of charge and discharge of the battery and to adapt the output voltage of the battery to the load [5].

The parameters of the PI controllers used are grouped in the table below:

Table- V: Table Ziegler and Nichols Tuning

Parameters of PI controller	*Kp*	*Ti*
Parameters of PI controller for SEPIC converter	3.21	0.0023
Parameters of PI controller for BOOST converter	9	0.0016

D. Principle of generating the PWM

PWM (Pulse With Modulation) is a voltage or current cutting technique that allows quasi-sinusoidal forms. The aim is:

- Adjust the amplitude and frequency of the fundamental.

-Reject irreversible harmonic to high frequencies.

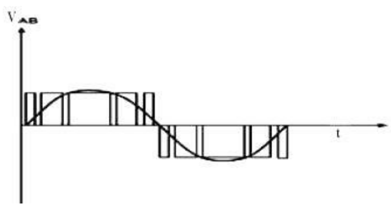

Fig.13. Pulse width modulation

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In this inverter, we have a power bridge with 04 transistors: Q1, Q2, Q3 and Q4. The rectangular voltage obtained between A and B is then filtered to obtain at the output of the apparatus a sinusoidal voltage with a low distortion rate.

Two transistors operate with a low frequency, ie 50 Hz (Q3 and Q4). Two other transistors (Q1 and Q2) operate at high frequency (20 kHz) of the sinusoidal PWM signal.

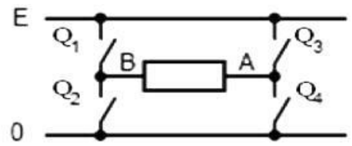

Fig.14. Transistor Power Bridge

IV. SIMULATION RESULTS

The results found in this section are developed using Matlab / SIMULINK software. The battery voltage used has a nominal voltage of 24V. A resistive load of 10 Ω is used for the simulation.

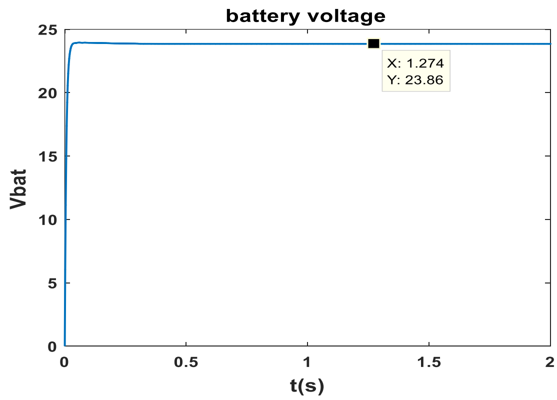

Fig.15. The battery voltage

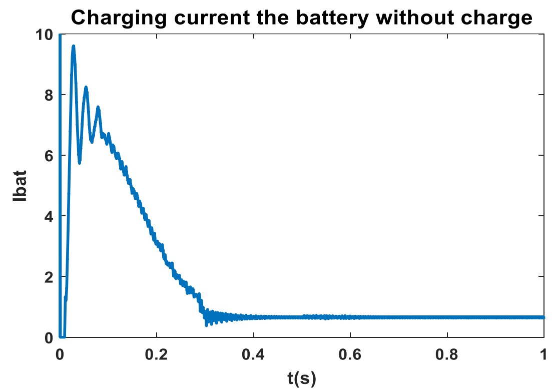

Fig.16. Charging current of the battery without charge

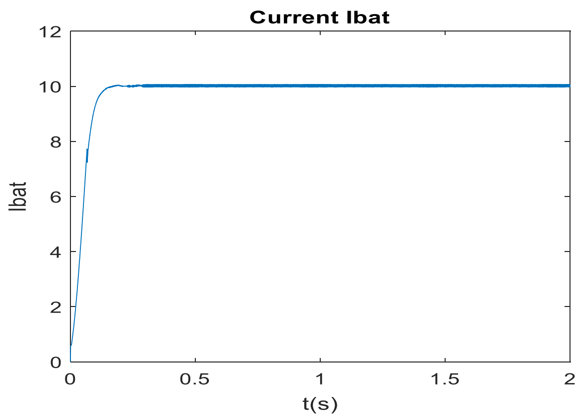

Fig.17. Ibat current of the battery with charge

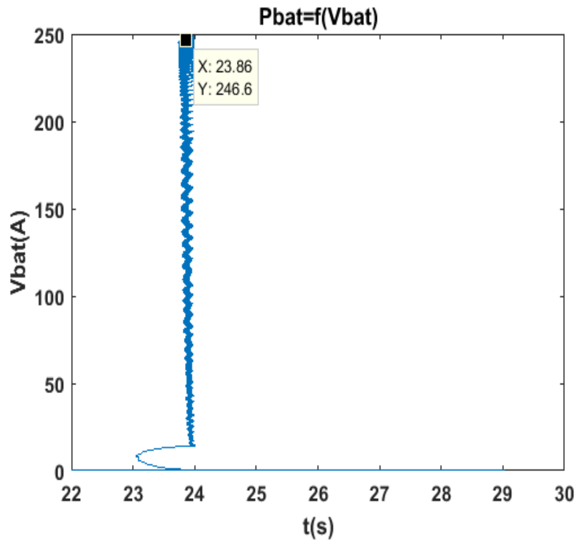

Fig.18. The power Pbat according to Vbat

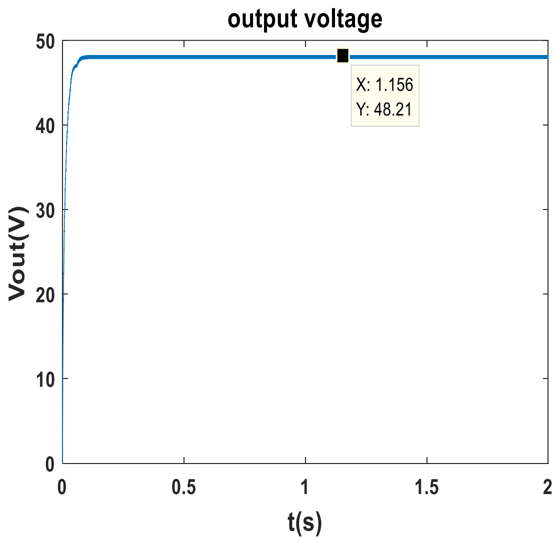

Fig.19. The output voltage of the PV system

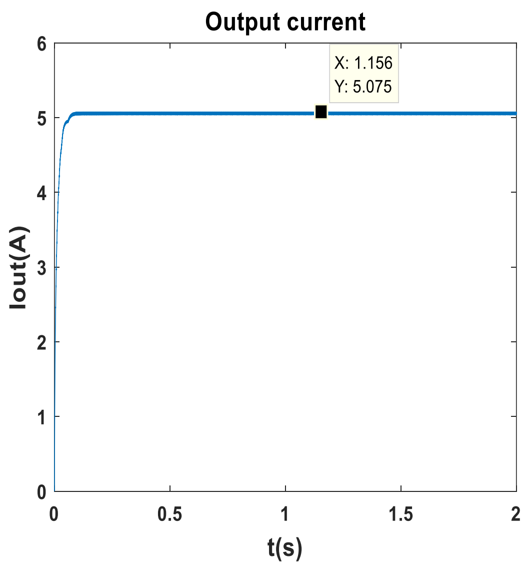

Fig.20. Output current of the PV system

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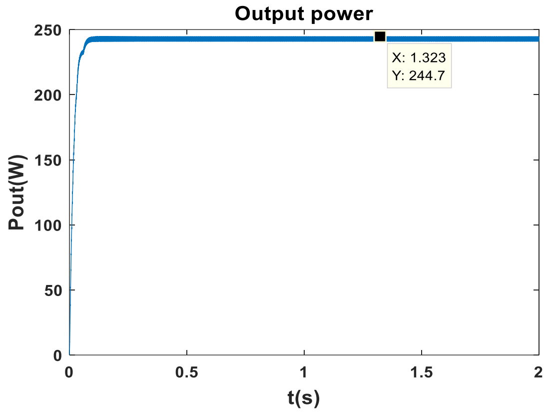

Fig.21. Output power of the PV system

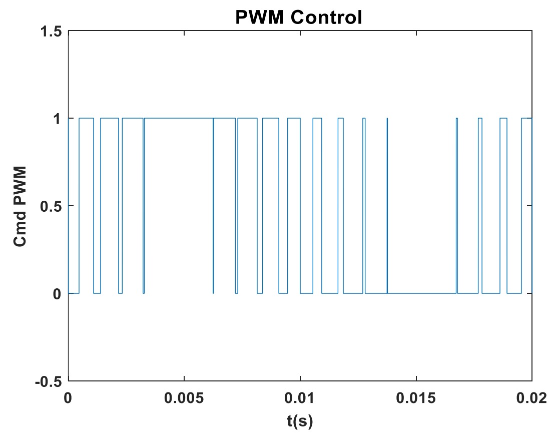

Fig.22. PWM Command

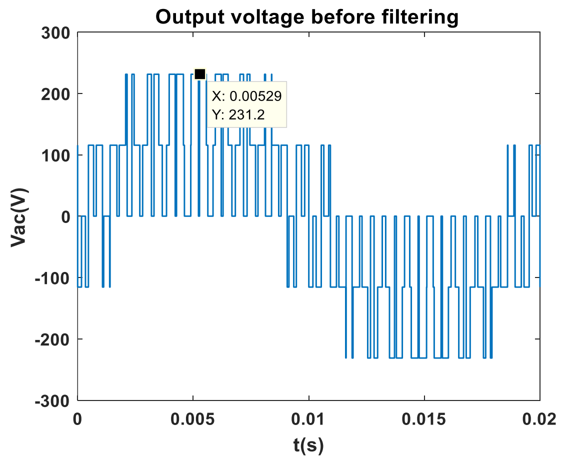

Fig.23. Inverter output voltage before filtering

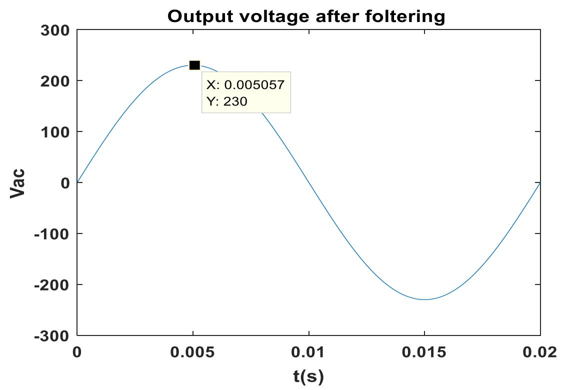

Fig.24. Inverter output after filtering

V. DISCUSSION

The simulation results have shown that the charge-discharge regulator of the battery has good regulating capacity by the use of the SEPIC converter, the voltage Vbat is of the order of 23.86 V with a response time of 0.08 s and a ripple rate of 1%. The current Ibat with charge is stabilized at 10, 34A that is to say with a power of 246.7124 and a yield of 98.6%. For the boost converter model "Figure 16" shows the output voltage response of the BOOST converter for an input voltage of 24 V with an output load of 10 Ω. The controller PI stabilizes the output voltage Vs compared with the reference voltage 48V. According to the simulation, after 0.1s, the output voltage is restored to its reference value with a ripple rate of 1% in the steady state. The efficiency of the converter is of the order of 98%, i.e. the output power is of the order of 244,7W.

For the inverter after filtering, the output voltage is of the order of 230Vac with a THD = 10%.

The following table summarizes the main specifications of the PV and previously studied MPPT algorithms.

Table-VI: Analysis the performance of PV System

Parameters PV System	***Value***
Maximum power extracted	244.7W
Voltage at the battery terminal Vbat(V)	24V
Output voltage Vout(Vdc)	48,21V
Output voltage Vout(Vac)	230V
Response time Vbat	0.1s
Response time Vs	0.1s
% of Overshoot Vs	1%
% of Overshoot Vbat	0%
Efficiency%	98%
Observation	GOOD in response and power transmitted

VI. CONCLUSION

In this article we have described the main elements of the autonomous PV system. Then, we dimensioned the parameters of the PI correctors by the use of the state space method to define the transfer function of the following converters: SEPIC and BOOST and after the use of the Ziegler and Nichols method to define the values of Kp and Ki. Finally, we finished with a simulation of the autonomous PV system. The results of the simulations show that the system has an efficiency of 97% with a ripple rate of 1% and a response time of 0.1s. The use of the SEPIC converter with the MPPT command followed by the PI controllers shows that the system has good regulation capacity, the voltage Vbat is of the order of 23.86 V with a response time of 0.08 s and a ripple rate of 1%. The current Ibat is stabilized at 10, 34A that is to say the power is of the order of 246.7124 and the efficiency is equal to 98.6% .The BOOST converter is used to adapt the output voltage of converter SEPIC at the voltage demand by the load, the result shows that the converter has good performance: an efficiency of the order of 97% that is to say an output power of 242W for a load of 10Ω and finally the single-phase inverter is used to supply alternative loads..

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