CONTROL OF GRID-CONNECTED PHOTOVOLTAIC INSTALLATION WITH BATTERIES AND SUPERCAPACITORS SYSTEM STORAGE

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Abstract: *this paper presents a control of grid-connected photovoltaic installation with storage system (electrochemical batteries, Supercapacitors); the objective of this system is to supply prescribed active photovoltaic power to the grid in different atmospheric conditions (Temperature, illumination). The storage systems make it possible to ensure the desired active power injected to the grid in any time, so the continuation service is achieved. This presented work focuses on decupled active and reactive power strategy, which makes it possible to control the level of the active and reactive power injected to the electrical supply network. Simulation results illustrate the performances obtained.*

Keywords: *Photovoltaic panels, PV, MPPT, battery, supercapacitor, active and reactive power control, grid-connected.*

1. Introduction

With the decrease of conventional energy sources and the growing problem of environmental pollution, the research and utilization of the renewable energy, such as solar energy, wind energy as so on, has been concerned with more and more attention [1].

PV power is becoming more prevalent as its cost is becoming more competitive with traditional power sources.

However, the utilization of dedicated energy storage systems needs to be taken into account because of the intermittent nature of the PV generation. Energy storage systems can open the possibility to employ renewable energy sources able to operate in stand-alone mode, grid-connected mode, and mode transitions from stand-alone to grid, or vice versa in micro-grid systems [2].

In this work we proposed a basic photovoltaic station with four electronics converter and (batteries and Ultracapacitors) storage system connected to the grid, this structure is controlled for prescribed active and reactive power to the grid.

The system performance has evaluated in rigorous situation to prove the feasibility and the simplicity of this control.

2. Photovoltaic generator model

Starting from the widely known photovoltaic cell electrical equivalent circuit [3] (Fig.1), an equivalent model for a more powerful PVG made of an (N_s x N_p) array of PV cells, is established [4] [5]:

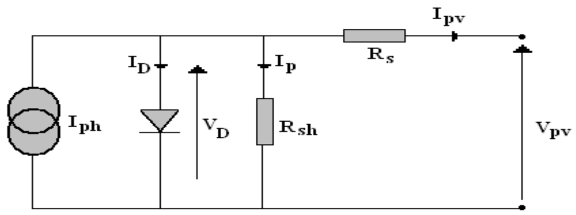


Fig.1. Simple model of the photovoltaic cells.

$$I_{pv} = I_{ph} - I_D - I_p \quad (1)$$

I_D expression being deduced from the semiconductor diode theory, the above relation may be detailed as:

$$I_{pv} = I_{ph} - I_o(\exp(\frac{V_{pv} + R_s I_{pv}}{nKT/q}) - 1) - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (2)$$

Where, I_{ph} is the light generated current (A), I_o the PV cell saturation current (A), q the electron charge (q = 1, 6 10^{-19} C), K the Boltzmann constant (K = 1, 38 10^{-23} J/K), n the cell ideality factor, T the cell temperature. R_{sh} and R_s are pure parasitic resistances characterizing respectively parallel current leakage and series connecting circuit.

In general, for a PVG involving an array of N_S cells connected in series and N_P in parallel, its output voltage current relation may be deduced from the basic cell equation (2) as follows [4] [5]:

$$I_{pv} = N_p I_{ph} - N_p I_o (\exp(\frac{q(V_{pv} + \frac{N_s}{N_p} R_s I_{pv})}{nKTN_s}) - 1) - \frac{V_{pv} + \frac{N_s}{N_p} R_s I_{pv}}{\frac{N_s}{N_p} R_{sh}} \quad (3)$$

From (2), an already temperature dependence of the cell external characteristic is established. Furthermore, all the cell parameters (I_o, n, R_s and R_{sh}), are equally temperature related. However, semiconductor diode theory, suggests that the most significant temperature effect comes from the reverse saturation current I_o. Variation of its value I_o (T) with working temperature T, is usually evaluated relatively to its evaluated value I_o (T_r) at a reference temperature T_r [3].

$$\frac{I_o(T)}{I_o(T_r)} = (\frac{T}{T_r})^3 \exp[\frac{qE_g}{nK}(\frac{1}{T_r} - \frac{1}{T})] \quad (4)$$

Where: Eg is the cell material band gap, supposed here no temperature dependant, and k is the Boltzmann constant.

The value of saturation current Io (T_r), may be evaluated through the open circuit voltage V_{oc} (T_r) and the short circuit current I_{SC} (T_r) deduced from (2).

$$I_o(T_r) = \frac{I_{sc}(T_r)}{(e^{\frac{qV_{oc}(T_r)}{nkT}} - 1)} \quad (5)$$

The equation of the illumination current brought back to the reference conditions (G_r = 1000W/m², T_r =25C°) is given as follows:

$$I_{ph} = [I_{cc} \frac{G}{G_r} + I_t (T - T_r)] \quad (6)$$

I_t: Temperature coefficient of short-circuit current.
G_r: The reference illumination.
G: The actually illumination.

The model of the PVG precedent is implemented in environment Matlab/Simulink as indicates the (Fig.2).

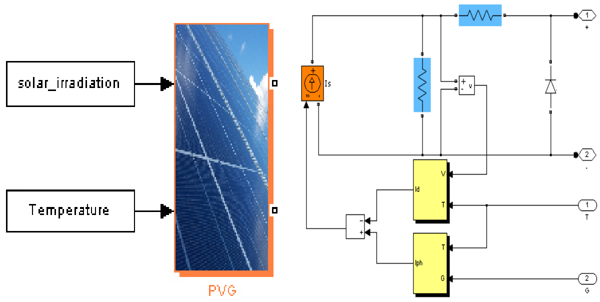


Fig.2. Structure of the PVG Simulink model.

The main external reference characteristics of the PVG are established using the identified perturbation inputs (solar illumination, temperature) as parameters (Fig.3, 4, 5).

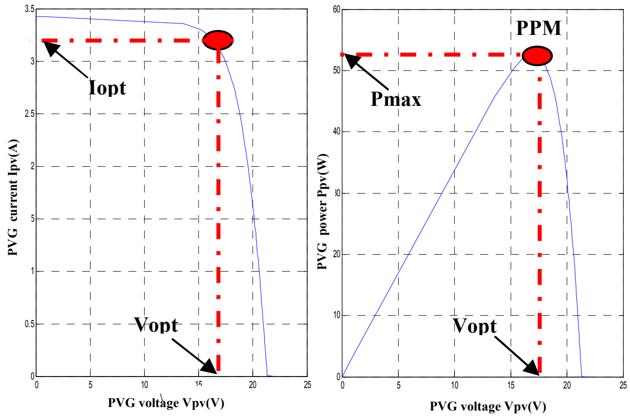


Fig.3. PVG (current – voltage) and (power – voltage) characteristic for standards conditions.

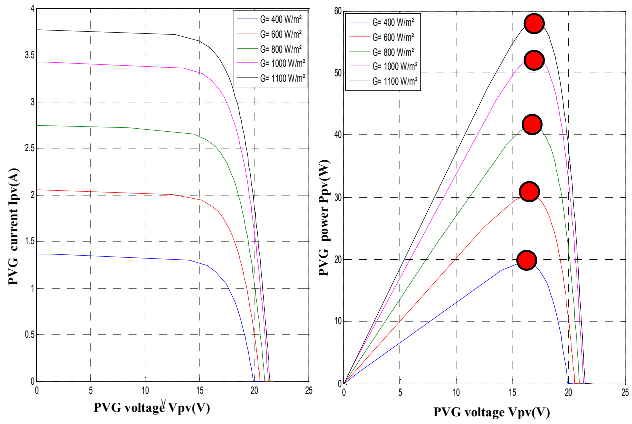


Fig.4. PVG (current – voltage) and (power – voltage) characteristic for different solar illumination, T=25C°.

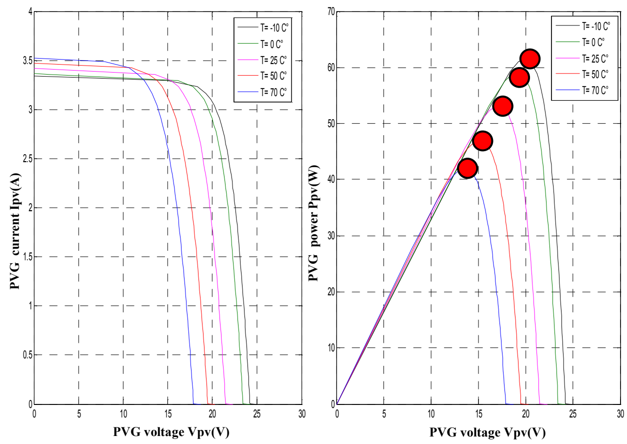


Fig.5. PVG (current – voltage) and (power – voltage) characteristic for different temperature, G=1000W/m².

3. Simulation model

One of the principal disadvantages of solar energy is its intermittent character. For a permanent use, it is thus necessary to store part of produced energy. There are several methods of storage: in water form, hydrogen, a Supercapacitors, or electrochemical battery [6].

3.1. Batteries

The battery block of MATLAB-SIMULINK "Sim Power Systems" (Fig.6) implements a generic dynamic model parameterized to represent most popular types of rechargeable batteries (Lead-Acid, Lithium-Ion, Nickel-Cadmium, Nickel-Metal-Hydride) [7].

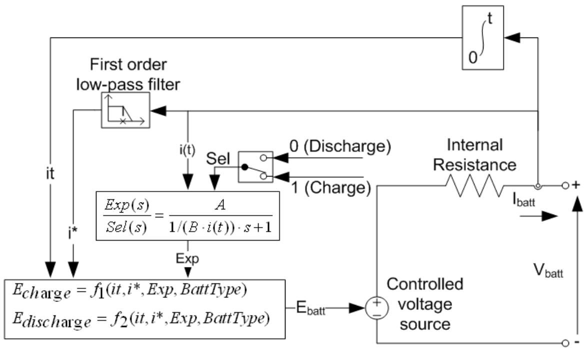


Fig.6. battery model [7].

The charge and discharge equations of the lead acid battery are given [7]:

Charge:

$$E_{batt} = E_o - R.i - K\frac{Q}{i_t - 0.1Q}i^* - K\frac{Q}{Q - i_t}i_t + Exp(t) \quad (7)$$

Discharge :

$$E_{batt} = E_o - R.i - K\frac{Q}{Q - i_t}(i_t + i^*) + Exp(t) \quad (8)$$

$$\dot{Exp}(t) = B.|i(t)|.(-Exp(t) + A.sel(t)) \quad (9)$$

Where:

Sel (t)= charge or discharge mode.
Exp(t)= exponentiel zone voltage (V).
E_{batt}= nonlinear voltage (V).
V_{batt} = battery voltage (V).
E_0 = battery constant voltage (V).
K = polarization constant (V/Ah) or polarization resistance.
Q = battery capacity (Ah).
i_t = actual battery charge (Ah).
A = exponentiel zone amplitude (V).
B = exponential zone time constant inverse $(Ah)^{-1}$.
R = internal resistance (Ω).
i = battery current (A).
i^*= filtered current (A).

3.2. Supercapacitors

The simple Supercapacitors model used in this work is shown in (Fig.7). This model is established by neglected the slow model branch of R. Bonert and L. Zubieta. [8], [9].

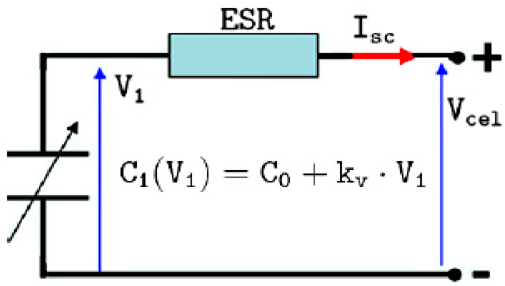


Fig.7. Supercapacitors model.

This model consists of:

- ESR: the internal resistance of the element where represent the auto discharge.
- The principal storage branch.

Where:

C_0: constant capacitor.
K_v: constant.
V_1: the voltage of the variable capacitor element.

4. Topology of the grid connected photovoltaic system

The photovoltaic system consists of (Fig.8):

1- Photovoltaic panels.
2- Means of storage: (batteries, Supercapacitors).
3- DC/DC converters.
4- DC/AC converter (inverter).
5- Filter.
6- Transformer for increasing the alternative voltage.

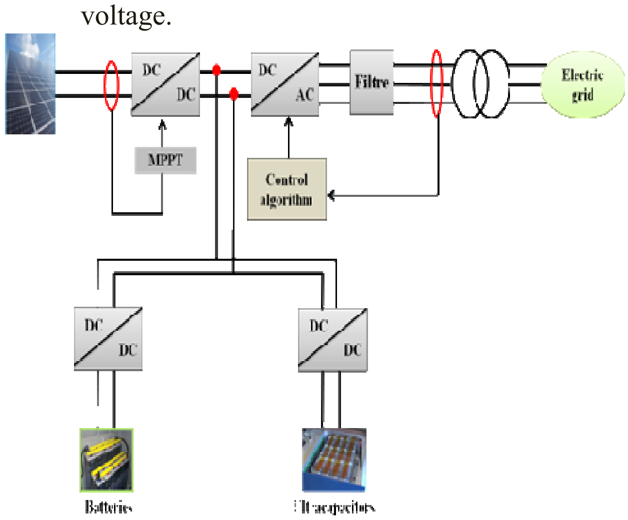


Fig.8. Global architecture of Grid-connected PV system

The photovoltaic panels used in this work are a UDTS50 types (Fig.9).

Standard illumination G (W/m²)	1000
standard Temperature T (C°)	25
Short-circuit current I_{cc}(A)	3.43
Open circuit voltage V_{co}(V)	21.28
Optimal voltage V_{opt}(V)	16.65
Maximum power P_{max}(W)	52.66
Form Factor (%)	72
Output (%)	11
Series resistor R_s(Ω)	0.4
Cell surface S (cm²)	10*10
Number of the cell	36

Fig.9. UDTS50 photovoltaic panels.

The DC/DC converter associate to the photovoltaic generator is a boost chopper controlled to extract the maximum power for different values of illuminations and temperature.

The two other DC/DC converters are a Buck-Boost chopper using to ensure the power flow between the grid and the storage system.

The inverter is controlled to ensure the transfer of the produced photovoltaic power.

The storage systems consist of electrochemical batteries and Supercapacitors.

5. Control strategy

The control system is composed of three parts, the control of the boost converter, the two Buck-Boost converter and the three phase inverter.

5.1. Boost chopper control

Due to its nonlinear external current–voltage characteristic, the PVG maximum power output varies with its operating point. The latter being equally load related, this occurs even for a given solar irradiation and temperature. In this case only a unique load value may ensure the optimum operating point in terms of maximum power extraction from the PVG, which output voltage and current are then at their respective optimal values (V_{opt}, I_{opt}). Generally, all the inputs defining the optimum operating point of the PVG (Solar irradiation, temperature and load, shading being a particular situation), are imposed. However, it is known in power DC electrical circuits, that a switching DC-DC electronic power converter may be an efficient impedance adaptor tool (Fig.10). Hence, it may be used to adjust the equivalent load impedance to the needed value for PVG optimal operating point, whatever are the solar irradiance, temperature and eventually shading rate [3].

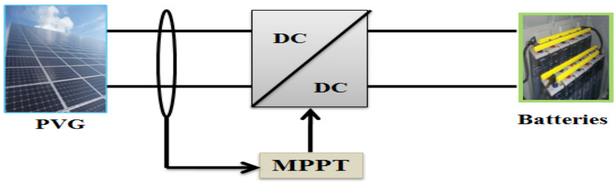


Fig.10. Control of the boost chopper.

The MPPT algorithm used is a classical one and will not be detailed in this paper.

5.2. Buck Boost Control

The DC/DC bidirectional converter used for controlling the two storage system (batteries, Supercapacitors) is shown in (Fig.11).

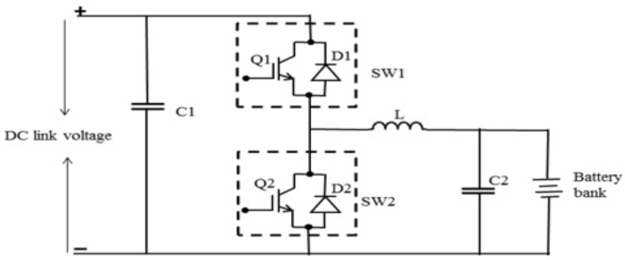


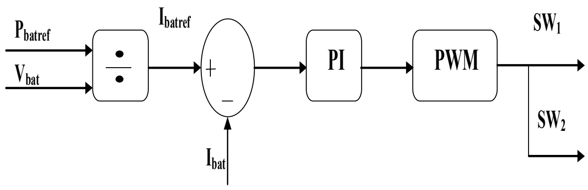
Fig.11. Bidirectional DC/DC converter.

The battery and Supercapacitors power are given such as [7]:

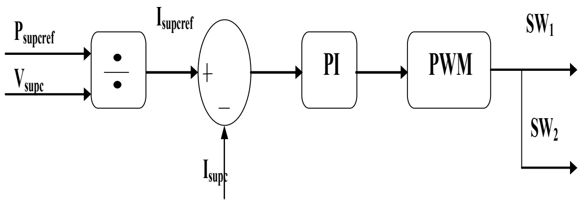
$$P_{bat} = V_{bat} I_{bat} \quad , \quad P_{\sup c} = V_{\sup c} I_{\sup c} \qquad (10)$$

So: $$I_{bat\_ref} = \frac{P_{bat\_ref}}{V_{bat}} \quad , \quad I_{\sup c\_ref} = \frac{P_{\sup c\_ref}}{V_{\sup c}} \qquad (11)$$

With: $$P_{bat\_ref} + P_{\sup c\_ref} = P_{storage} \qquad (12)$$



a. Battery Buck Boost control.



b. Supercapacitors Buck Boost controls.

Fig.12. Batteries and Supercapacitors control.

5.3. Inverter control

The objective of this control is to impose the active and reactive power injected to grid.

The diagram of the algorithm used in this work is shown in Fig.13.

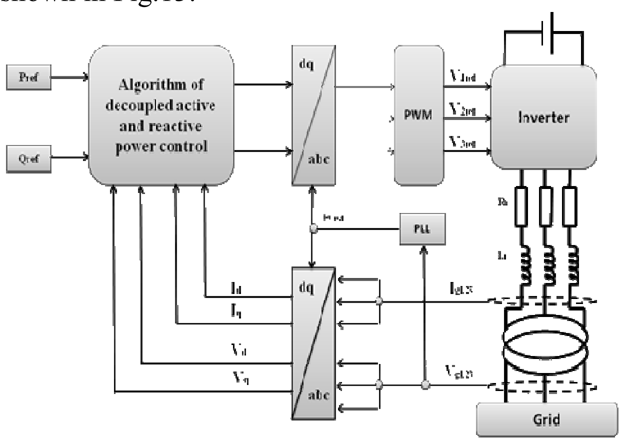


Fig.13. Bloc diagram of the used power control algorithm.

1. PLL Control

Various disturbances can occur on the electrical supply network, the objective of synchronization system is to reconstitute information on the direct component of the fundamental voltage.

The principle of the three-phase PLL (Fig. 14) consists in applying an inverse Park transformation to the grid voltages. The component V_q generated by this transformation is controlled to zero by action on the estimation angle of Park (θ_{est}).In mode established θ_{est} is equal to the angle of the network θ.

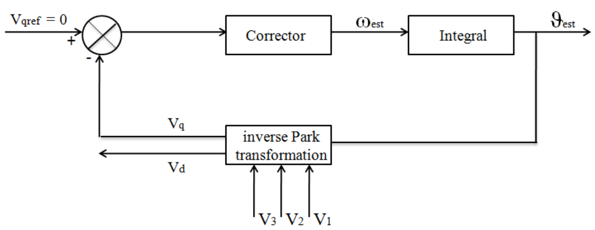


Fig.14. Principe of three phases PLL.

By using the park transformation and trigonometric methods, the V_d and V_q voltage can be written such:

$$\begin{cases} V_{dr} = \sqrt{\frac{3}{2}} V_m \cos(\theta - \theta_{est}) \\ V_{qr} = -\sqrt{\frac{3}{2}} V_m \sin(\theta - \theta_{est}) \end{cases} , (\theta - \theta_{est}) = \delta \qquad (13)$$

The objective of the control is to cancel δ to obtain the frequency and the voltage angle at the connection point.

To be able to use the traditional techniques of corrector adjustment, it is necessary to linearize the PLL.

Thus, if the system error is regarded as very small, the relation between this error and the error of estimation phase will be:

$$V_{qr} = -\sqrt{\frac{3}{2}} V_m \sin\delta \cong -\sqrt{\frac{3}{2}} V_m \delta \qquad (14)$$

The diagram of three-phase PLL regulation is represented in (Fig.15) [10]:

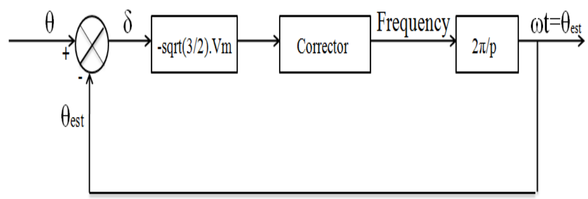


Fig.15. PLL control system.

2. Power control

The active and reactive power (P, Q) can be both expressed by using Park components of supply voltage (V_d , V_q) and line current (I_d , I_q) as follows [11]:

$$\begin{cases} P = V_d I_d + V_q I_q \\ Q = V_d I_q - V_q I_d \end{cases} \qquad (15)$$

In DC bus, the reference of the active power is established such as:

$$P_{pv} + P_{bat} + P_{\sup c} = P_{ref} + P_{dcref} \qquad (16)$$

So:

$$\begin{cases} P_{ref} = P_{pv} + P_{bat} + P_{\sup c} - P_{dcref} \\ Q_{ref} = 0 \end{cases} \qquad (17)$$

The unity power factor is obtained simply by setting the reactive power reference null. We can also generate or absorb (Q_{ref}<0 or Q_{ref} >0).

3. DC Control

To manage the power flow in this system, we need to control the DC bus in any time [12] (Fig.16).

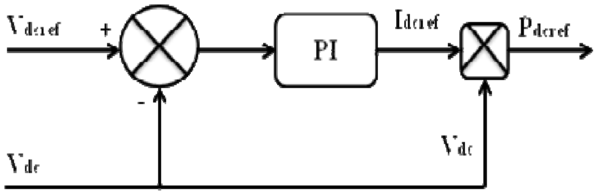


Fig.16. DC control.

3. DC Control

The vector current control in Park reference frame is carried out by using the synchronized reference with the grid voltage [11]. The electric equations of the filter (R_r , L_r) connected to the grid are given bellow:

$$\begin{cases} V_d = R_r I_d + L_r \dfrac{dI_d}{dt} - \omega_s L_r I_d + V_d \\ V_q = R_r I_q + L_r \dfrac{dI_q}{dt} - \omega_s L_r I_q + V_q \end{cases} \quad (18)$$

The reference currents (I_{dref}, I_{qref}) which allows setting the desired reference active and reactive powers (P_{ref} , Q_{ref}), as follows [11].

$$\begin{cases} I_{dref} = \dfrac{P_{ref} V_d - Q_{ref} V_q}{V_d^2 + V_q^2} \\ I_{qref} = \dfrac{P_{ref} V_q - Q_{ref} V_d}{V_d^2 + V_q^2} \end{cases} \quad (19)$$

The full diagram of a decoupled active and reactive power algorithm [12], [13] is shown in (Fig.17).

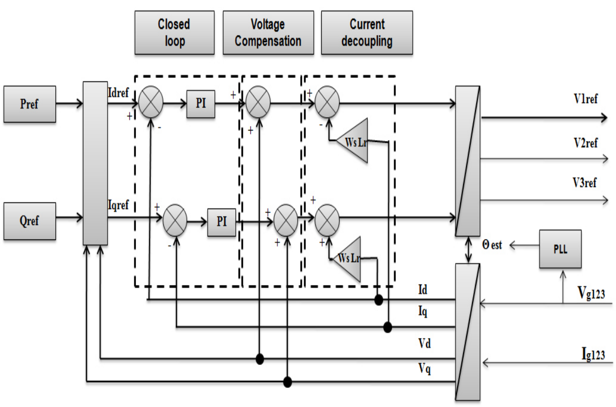


Fig.17.Diagram of the decoupled active and reactive power control.

6. Simulations results

In this section, the photovoltaic grid connexion system is simulated using SIMULINK-MATLAB.

Several numeric simulations of the proposed system were accomplished for different situations (Power injected and illuminations values). The most important parameters of the converter are shown in Table. I

TABLE I
PARAMETER VALUES

Quantity	Values
Batteries voltages (V)	12*20
Supercapacitors voltage (V)	2.7*100
Transformer (Y/Y) (V)	220/380
Electric grid (V)	220/380
Commutation frequency (Hz)	10000

The main simulation results are given in (Fig.18 to 25).

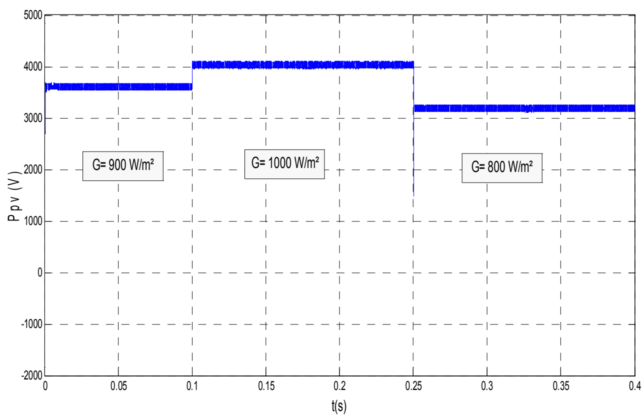


Fig.18. photovoltaic power for different illumination values.

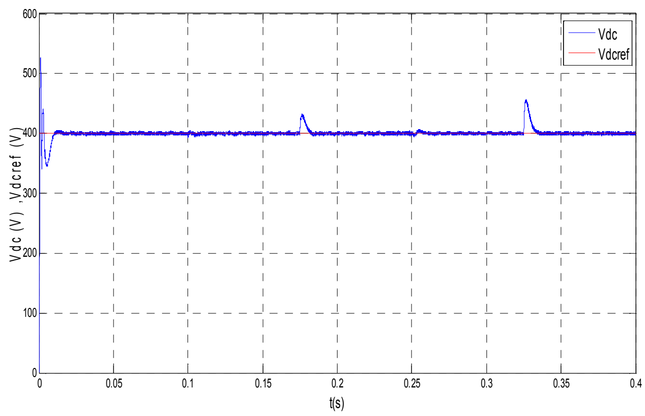


Fig.19. DC voltage control.

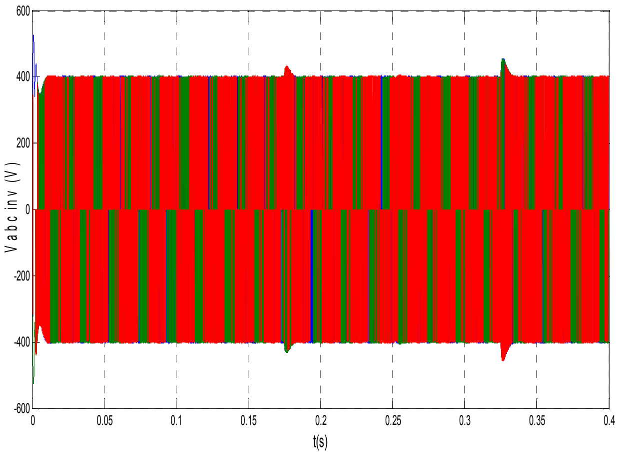


Fig.20. the three phase voltage of the inverter.

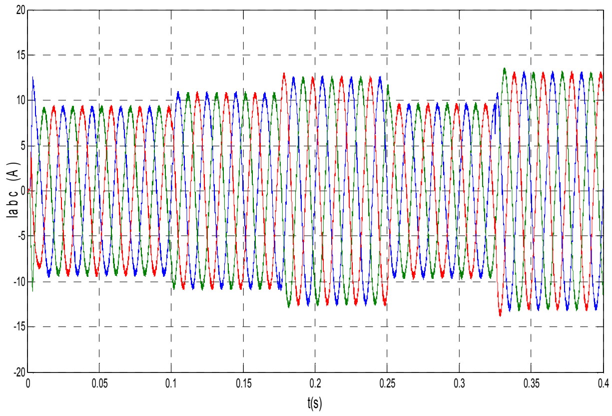


Fig.21. Form of the current injected to the grid.

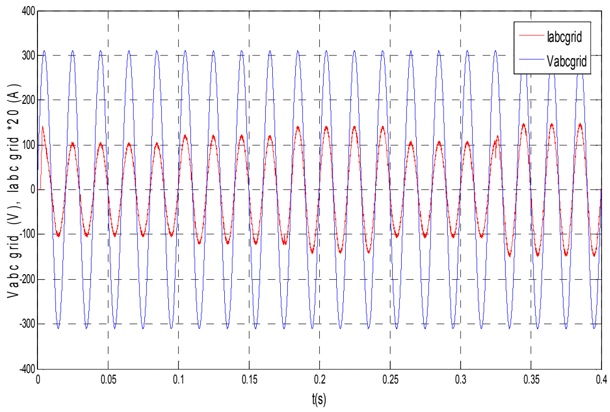


Fig.22. Form of the voltage and current injected to the grid.

The power variation of the storage (batteries, Supercapacitors) system is shown in Fig.23.

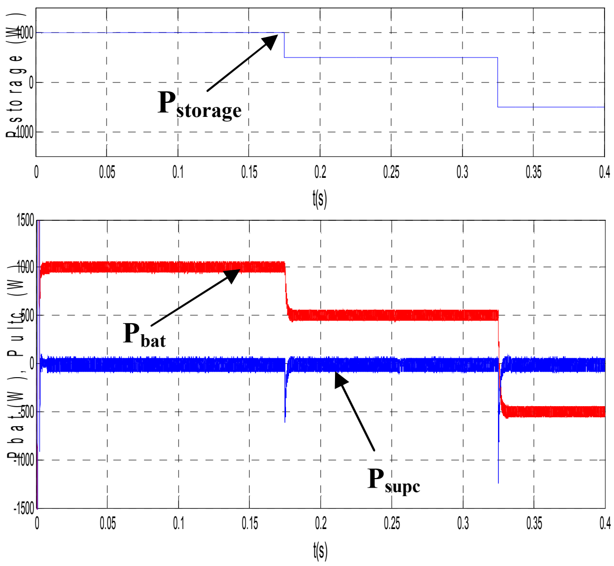


Fig.23. Variation of the storage system power.

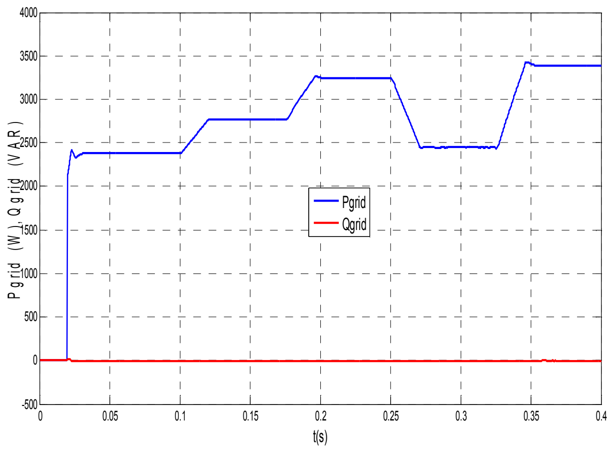


Fig. 24.Active and reactive power injected to the grid.

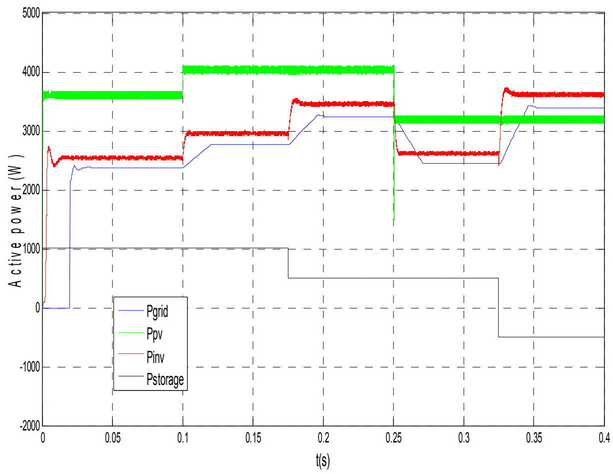


Fig.25.Variation of the active power in the photovoltaic system.

The control device makes it possible to impose the values desired of the active and reactive powers (image of current), with a very acceptable dynamics.

In the illumination reference, we have imposed betwen $0<t<0.1s$ ($G=900W/m^2$), $0.1s<t<0.25s$ ($G=1000W/m^2$), and $0.25<t<0.4$ ($G=800W/m^2$). the MPPT control follow directely this variation.

The DC link is controlled at the refrence voltage imposed $V_{dc}=400V$, with very acceptable dynamics.

Since the reactive power is null, the interval between the voltage and the current is null (unit power-factor),(Fig.22).

When the storage power reference is imposed, the batteries power follow the permanent regime mode because it has a long constant time. In other way the Supercapacitors pursue the a transient mode.

When the produced photovoltaic energy is higher than the positive storage reference power imposed, the difference is injected to the electric supply network. If the storage reference power is negative, this values is added with the photovoltaic power and transfred to the grid.

6. Conclusion

In this paper, a simple control of grid-connected photovoltaic station with batteries and Supercapacitors storage system has been presented in order to inject the active photovoltaic power to the electrical supply network.

The storage system makes it possible to supplement the electrical power injected to the grid in the moments when the photovoltaic power is not sufficient, therefore the service continuity is ensured in all time.

The simulation results obtained of this approach show and confirm the reliability and the simplicity of this type of control.

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