Power Management of Grid Connected Photovoltaic Installation Assisted by Batteries and Water Pumping Energy Storage in Desert Location

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Abstract- In this study, we develop a power control of grid connected photovoltaic installation assisted by batteries and pumping energy storage. In desert location, the use of photovoltaic grid connected system must be a reliability solution, also, in remote area, the water pumping system present an efficacy key for alimented the agriculture by water with lower price. The aim of this work is to design and provide prescribed active power to electrical grid in various metrological circumstances and in presence of batteries and hydraulic water pumping system. To provide the electrical grid, the active and reactive powers must be controlled. Furthermore, batteries can be used to reimburse the power lack or to accumulate the surplus, in other hand; water pumping system is used when we have a surplus energy, so the photovoltaic power can be translated in water hydraulic energy for provide the agriculture and farmer by water. Several rigorous simulation and initially experimental tests have been realized to prove the reliability of the completed installation.

Keywords- photovoltaic, grid connected battery, pumping system, power control.

1. Introduction

With the growing demand of energy and the depletion of fossil energy, the world require to finding a new clean and sustainable energy sources. Renewable energy (solar, wind, biomass, geothermal energy…), could be solving significantly this problem. The solar or wind energy systems begin to take a big part of the electricity produced by the thermal and nuclear power plants. The conversion systems are various; they can be connected directly to the electrical grid, or on remote site (standalone applications) [1].

The random behavior of load demand and renewable sources production energy make the strategy management of the (supply-demand) balance difficult. A real way to eliminate partially this problem is to incorporate storage systems. For that, we can decrease significantly the fluctuations and improve the power distribution quality [1, 2, 3]. Several research papers published with varied topologies and strategies for on-grid photovoltaic system with batteries [4, 5, 6, 7, 8, 9]. PV system is connected to the grid through a DC/DC converter and inverter, for that, MPPT control has introduced in the first converter to extract maximum power from PV panels in all situations [10, 11, 12, 13, 14]. Moreover, decoupled current control is implemented to follow the active and reactive power independent control [4, 10]. The battery is an efficient key to balance the intermittency of PV power supply, also, bidirectional DC/DC converter has been used for controlling and optimizing the two battery operations mode (charge, discharge) [4, 15].

In arid area, Ghardaïa city, situated in the south of Algeria, about 600 Km south of the capital city; characterized by an enormous solar irradiations (duration

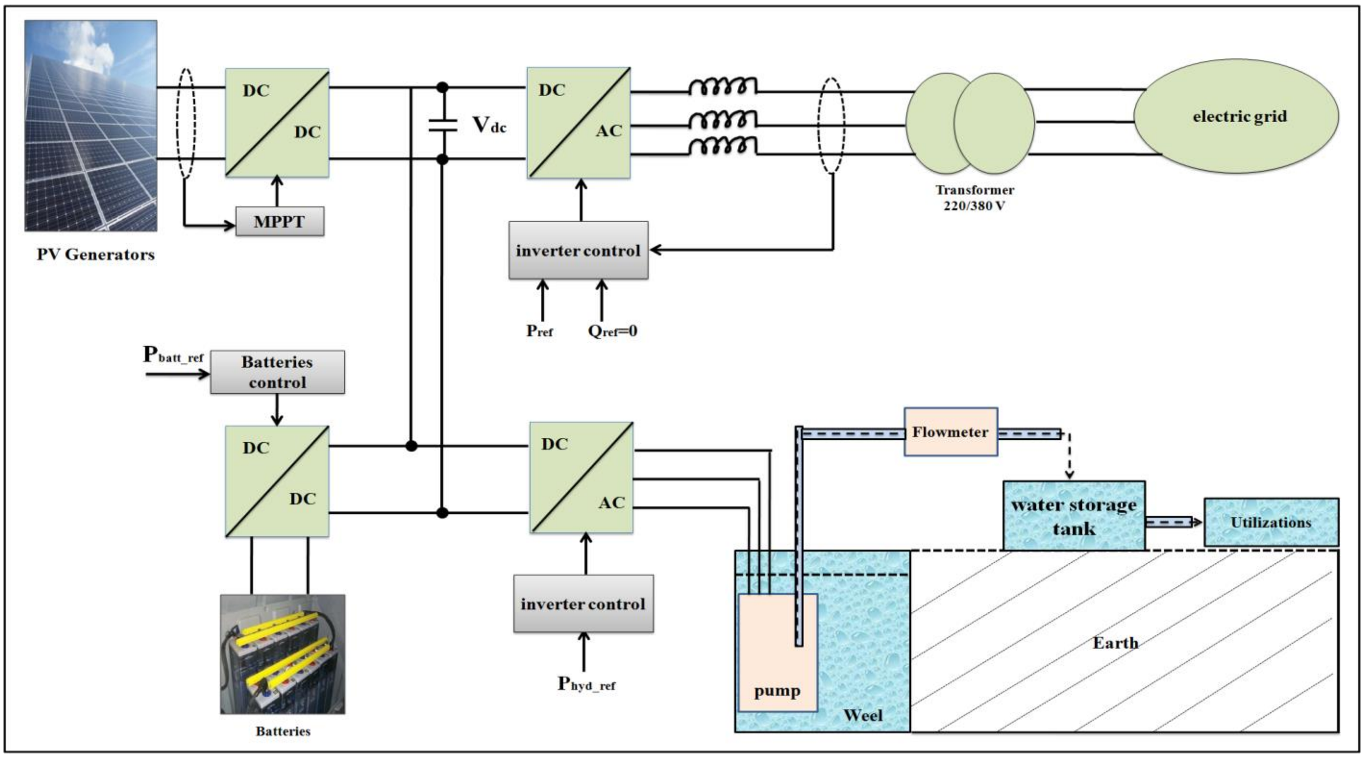


Fig. 1. Overall diagram of grid connected PV system with batteries and hydraulic stoarge energy.

3000 hours/year, 6000 Wh/m² mean annual global illuminations) [16]. For that, the grid connected PV installation become more and more competitive behind greatly attractive solar resources. Also, in remote areas, standalone photovoltaic water pumping system is one of the best choices for providing farmers by water and for reduces the electrical cost.

The motivation and idea of this study focus on developing, control and optimization of PV on-grid installation with electrochemical accumulators and hydraulic storage (water pumping) "Fig.1", for ensure:

- Support the grid power injected when the photovoltaic power produced is enough
- More photovoltaic storage power
- High storage flexibility
- Provisioning the farmer and agriculture by water.

This article is structured as follows: The PV generator, batteries, pumped systems are firstly introduced by a detailed modeling. In the second parts, an appropriate control was introduced for each installation parts for supervise the power between source, storage and electrical grid. Finally, the installation behavior is tested in several situations to examine and verificate the robustness of this strategy. Furthermore, we can ensure a smooth energy transfer in all situations and in presence of PV power random character.

2. System Platform Configuration and Modelling

2.1. Photovoltaic generator

The photovoltaic cell is modeled like an ideal current source "Fig.2"; it current I_{ph} is proportional to the incident illumination, also, connected with diode which represent P-N junction, R_s and R_{sh} are used for modeling series connecting circuit and parallel current leakage[11, 17, 18].

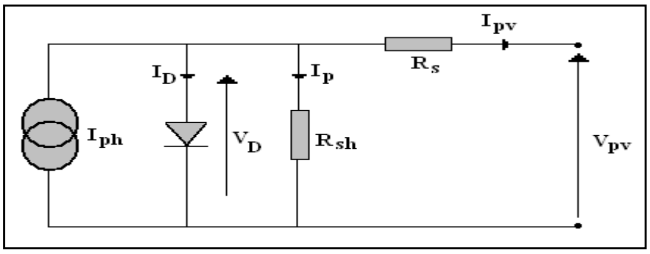


Fig. 2. Photovoltaic cell model.

From this circuit, the PV cell current can be expressed such as:

$$I_{pv} = I_{ph} - I_D - I_p \tag{1}$$

By using the expression of diode current theory, equation (1) becomes:

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

Which:

I_0 :	saturation current (A)
q :	electron charge (1.6 10^{-19} C)
K :	Boltzmann constant (1.38 10^{-23} J/K)
n :	Ideality factor
T :	Cell temperature

The PV cells produce a feeble power, for that, it is necessary to connect N_s cells in series and N_p in parallel. In this case, the PV model can be established such as [19]:

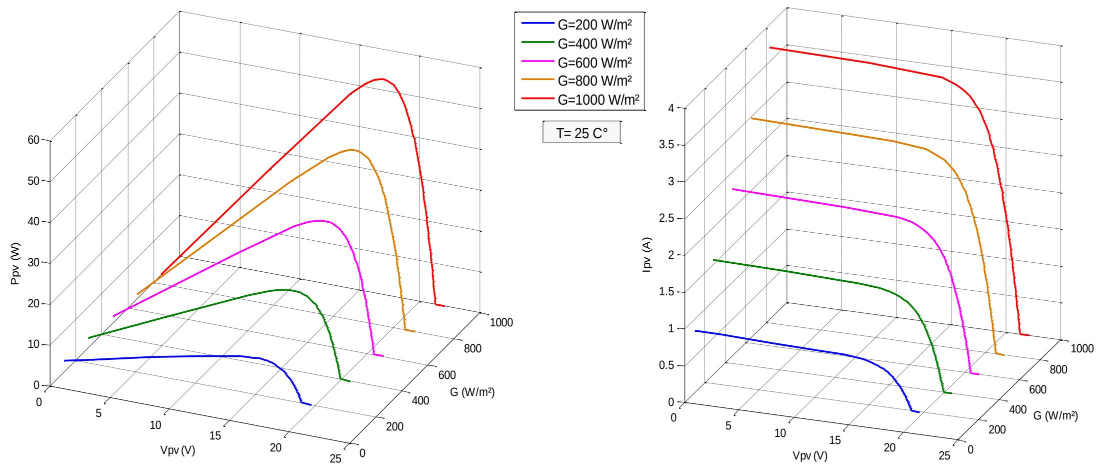


Fig. 3. External characteristic of photovoltaic panels for different irradiation values.

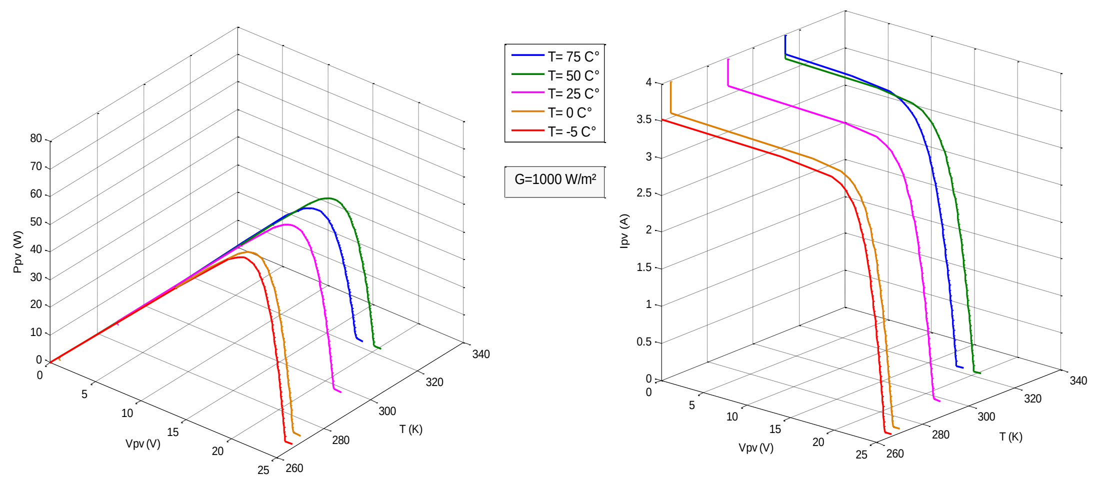


Fig. 4. External characteristic of photovoltaic panels for different temperature values.

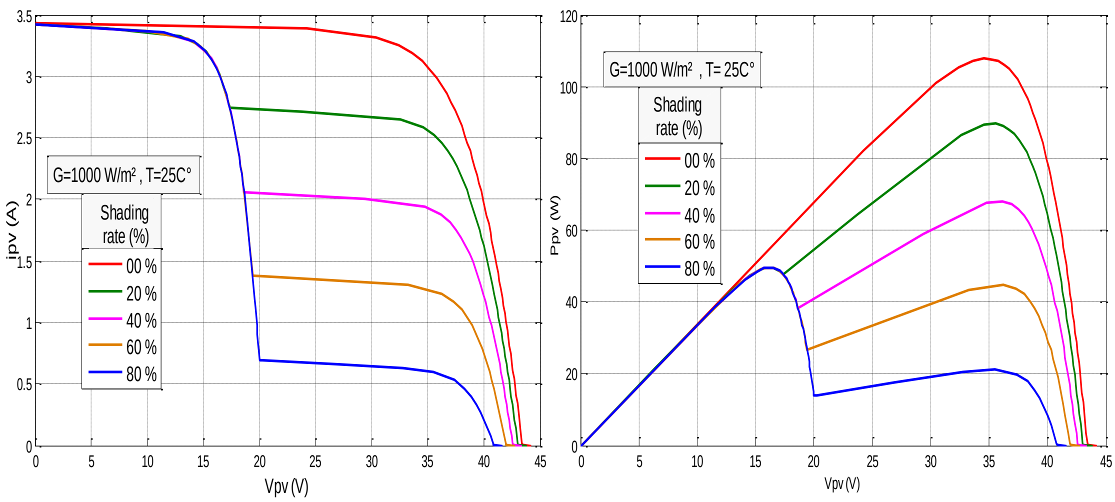


Fig. 5. External characteristic of two series photovoltaic panels for different values of shading rate (%) and standard conditions (G=1000W/m², T=25C°).

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

The most usually external characteristics of PV cell are shown in “Fig.3” and “Fig.4”, in shadow conditions, the behaviors will be change like demonstrated in “Fig.5”.

2.2. Battery

The battery store electrical energy in chemical form for returns it when the electrical demand is greater (night, insufficient illumination, shadow) then supply photovoltaic panel power. The battery model used in this study “Fig.6” consists of an internal resistance and voltage source controlled by charge and discharge models equations which are depending on different problem variations [15, 19].

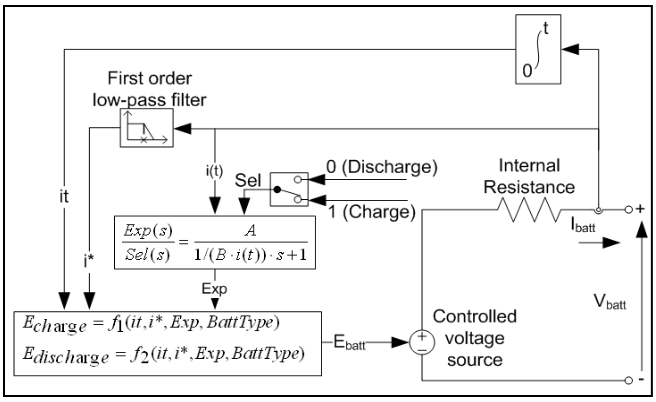


Fig. 6. Battery model [15].

2.3. Pumped storage system

The water pumping is the largest promising applications of the photovoltaic solar energy, the popular pumps used are the centrifugal pumps designed for a height total gauge relatively fixed, and the flow rate of this pump varies in proportion to the rotation speed. The centrifugal pump is composed on motor and pump.

2.3.1. Asynchronous motor

The mathematical model of an asynchronous motor can be established using d-q transformation like demonstrated in equations [20, 21, 22]:

$$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \\ V_{qs} = R_s I_{qs} + \dfrac{d\phi_{qs}}{dt} + \omega_s \phi_{ds} \\ 0 = R_r I_{dr} + \dfrac{d\phi_{dr}}{dt} - \omega_s l \phi_{qr} \\ 0 = R_r I_{qr} + \dfrac{d\phi_{qr}}{dt} + \omega_s l \phi_{dr} \end{cases} \quad (4)$$

$$\begin{cases} C_e - C_r = J\dfrac{d\Omega}{dt} + f\Omega \\ C_e = pL_m (I_{qs} I_{dr} - I_{ds} I_{qr}) \end{cases}$$

With:

d, q:	synchronous reference frame axes
R_s, R_r :	stator and rotor motor resistances
I_{ds}, I_{qs} :	d-q stator currents
ϕ_{ds}, ϕ_{qs} :	d-q stator flux
V_{ds}, V_{qs} :	d-q stator voltages
I_{dr}, I_{qr} :	d-q rotor currents
ϕ_{dr}, ϕ_{qr} :	d-q rotor flux
ω_s :	stator electrical pulsation
ω_r :	rotor electrical pulsation
L_m :	motor mutual inductance
P :	motor pole pairs number
C_e :	motor torque
C_r :	load torque
f :	friction coefficient
J :	total inertia
Ω :	mechanical speed

2.3.2. Centrifugal pump

The *H (Q)* characteristic of centrifugal pump is obtained using Pleider-Peterman model [23]. The multispeed can be expressed approximately by the following quadratic form:

$$H = C_1\omega^2 - C_2\omega Q - C_3 Q^2 \quad (5)$$

The pipe resistance characteristic can be given by:

$$H = H_s + K_{fr} Q^2 \quad (6)$$

The hydraulic power of the pump is given by:

$$P_h = \rho g Q H \quad (7)$$

The resistive torque is given by:

$$C_r = K_{ch}\omega^2 \quad (8)$$

With:

C_1, C_2, C_3	coefficients given by the manufacturer
H_s	pump static head
K_{fr}	canalization constant
K_{ch}	Proportionality constant.

3. Power Control Methodology

The studied system is composed of four subsystems (sources or consumption), hence, for carried out the globally power control we need a detailed consideration of each parts.

3.1. MPPT boost control

The photovoltaic generator is a non-linear power source; its external electrical characteristics output depend on several climatic factors such as: illumination, temperature and shading. Therefore, a judicious tracking of optimal point (MPP: Maximum Power Point) in real time must be realized to optimize the overall performance of the system. The DC/DC converters are used to follow the optimal point in all conditions with very high flexibility and better performance [19, 24].

From previous studies [13], we have many research algorithms for tracking the optimal point PPM (direct and indirect methods). The most commonly used are: Perturb & Observe and incremental conductance. In our work we use P&O algorithm implemented with boost converter "Fig.7", the control based on perturb of the PV voltage with low amplitude around it initial value and analyze the power behavior. If positive increment of the voltage creates an increase in the power, this means that the operating point is located in the left of the PPM. On the contrary, the power decreases, this implies that it is in the right. A similar reasoning can be performed when the voltage decreases [24, 25, 31].

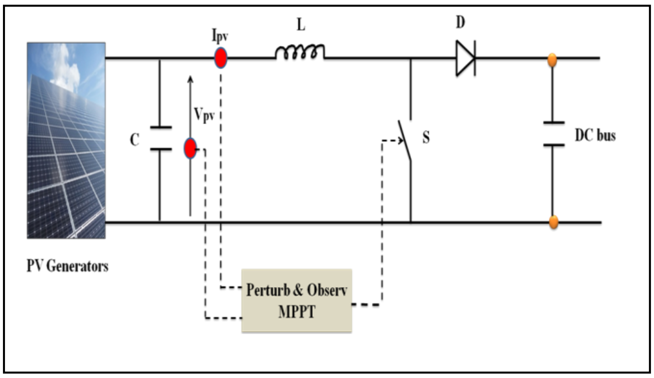


Fig. 7. Perturbe and Observ MPPT boost control

3.2. Batteries buck- boost control

The battery stores electrical energy in chemical form for return it when the electrical demand is greater (night, insufficient irradiations, shading). The power management for the two operating mode is secured by a bidirectional current converter [32]. The main components of this structure and algorithm control are shown in "Fig.8".

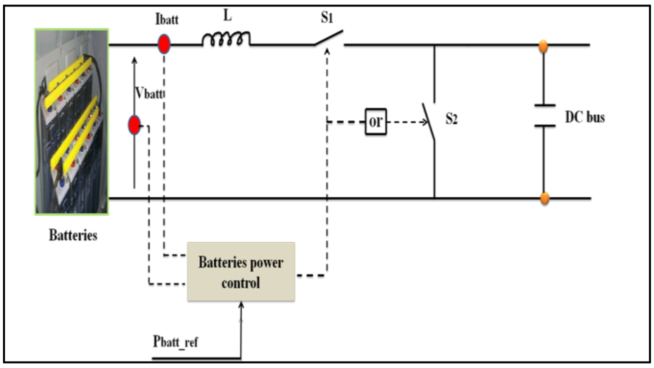


Fig. 8. Batteries Buck-boost control

The battery power is given such as :

$$P_{batt} = V_{batt} I_{batt} \tag{9}$$

So, the reference current is given:

$$I_{batt\_ref} = \frac{P_{batt\_ref}}{V_{batt}} \tag{10}$$

The control bloc is presented in " Fig.9"

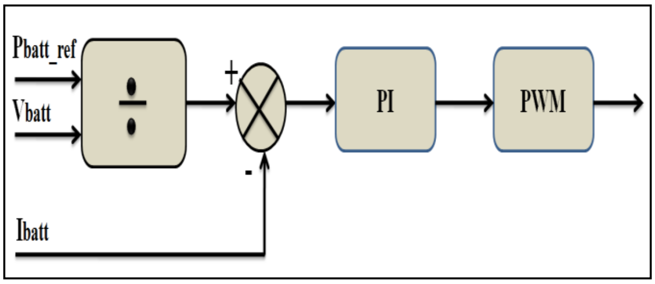


Fig. 9. Control bloc

3.3. Pumping inverter vector control

The vector control technique based on the three phase currents machine transformation in two orthogonal components (vectors) in Park transformation (d-q) frame. The first vector allows the adjustment of the motor magnetic flux, and the second regulate the torque. So, they are decoupled and the operation modes become similar to DC motor. The electromechanical torque can be established such as [26, 20, 21, 22, 33]:

$$C_e = \left(\frac{pL_m}{L_r}\right)\Phi_r I_{qs} \tag{11}$$

The motor flux is shown such as:

$$\Phi_r = \left(\frac{L_m}{T_r s + 1}\right) I_{ds} \tag{12}$$

The mechanical angle of park reference frame (d, q) can be calculated by:

$$\theta = \int (\omega_r + p\Omega)dt \qquad \omega_r = \left(\frac{L_m}{T_r \phi_r}\right) I_{qs} \tag{13}$$

The hydraulic power can be stored with this system is calculated such as:

$$P_{hyd} = \left(\frac{pL_m}{L_r}\right)\Phi_r I_{qs}\Omega \tag{14}$$

The Principe of the indirect vector control technique used is shown in "Fig.10".

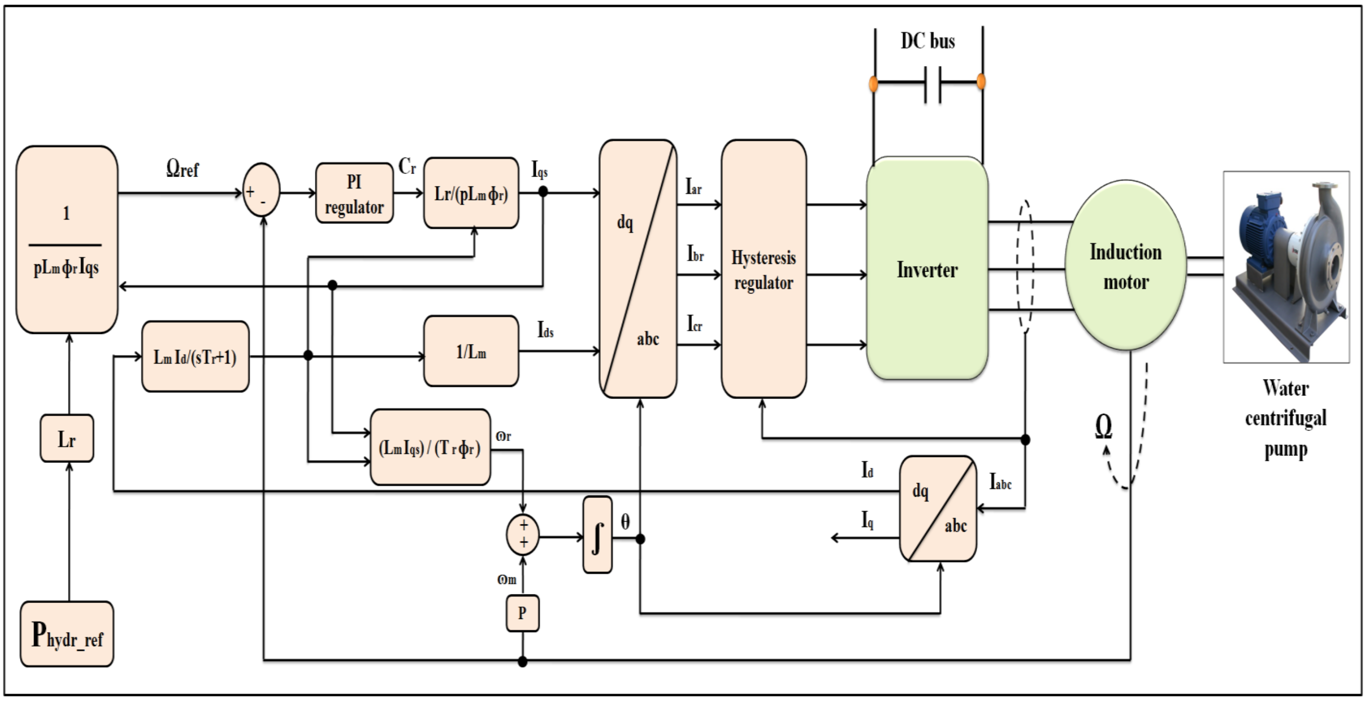


Fig. 10. Flux orientation Vector control method

3.4. Grid inverter control

To connect the PV voltage inverter in parallel with the grid and for work as a current source, it is necessary to use an inductive filter; the equivalent diagram peer phase is represented in “Fig. 11”:

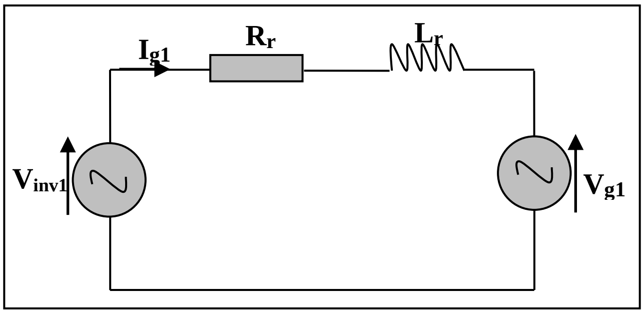


Fig. 11. equivalent circuit of one phase

From this circuit, the voltage equation is expressed such as:

$$L_r \frac{dI_{g1}}{dt} = V_{inv1} - V_{g1} - R_r I_{g1} \tag{15}$$

The complet system equation can be expresed:

$$\begin{bmatrix} \frac{dI_{g1}}{dt} \\ \frac{dI_{g2}}{dt} \\ \frac{dI_{g3}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_r}{L_r} & 0 & 0 \\ 0 & -\frac{R_r}{L_r} & 0 \\ 0 & 0 & -\frac{R_r}{L_r} \end{bmatrix} \begin{bmatrix} I_{g1} \\ I_{g2} \\ I_{g3} \end{bmatrix} + \frac{1}{L_r} \begin{bmatrix} V_{inv1} - V_{g1} \\ V_{inv2} - V_{g2} \\ V_{inv3} - V_{g3} \end{bmatrix} \tag{16}$$

In park frame, the equation system (16) become:

$$\begin{bmatrix} \frac{dI_{dg}}{dt} \\ \frac{dI_{qg}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-R_r}{L_r} & \omega \\ -\omega & \frac{-R_r}{L_r} \end{bmatrix} \begin{bmatrix} I_{dg} \\ I_{qg} \end{bmatrix} + \frac{1}{L_r} \begin{bmatrix} V_{dg} - V_{dg} \\ V_{qg} - V_{qg} \end{bmatrix} \tag{17}$$

If we use the laplace transformation, the equation (17) become:

$$\begin{cases} I_{dg} = \left(\frac{1}{L_r}(V_{dinv} - V_{dg}) + \omega I_{qg}\right) \frac{1}{P + \frac{R_r}{L_r}} \\ I_{qg} = \left(\frac{1}{L_r}(V_{qinv} - V_{qg}) - \omega I_{dg}\right) \frac{1}{P + \frac{R_r}{L_r}} \end{cases} \tag{18}$$

With:

V_{inv1} :	Inverter voltage
V_{g1} :	Grid voltage
I_{g1} :	Inverter current
R_r :	Inductive filter resistance
L_r :	Inductive filter inductance
V_{dinv} , V_{qinv} :	Inverter voltage in d-q transformation
V_{dg} , V_{qg} :	Grid voltage in d-q transformation
I_{dg} , I_{qg} :	Grid current in d-q transformation
ω :	Grid current pulse

The basic expressions of the active and reactive power can be delivered to electrical grid are demonstrated as follow [5, 6, 34]:

$$\begin{cases} P = V_d I_d + V_q I_q \\ Q = V_d I_q - V_q I_d \end{cases} \tag{19}$$

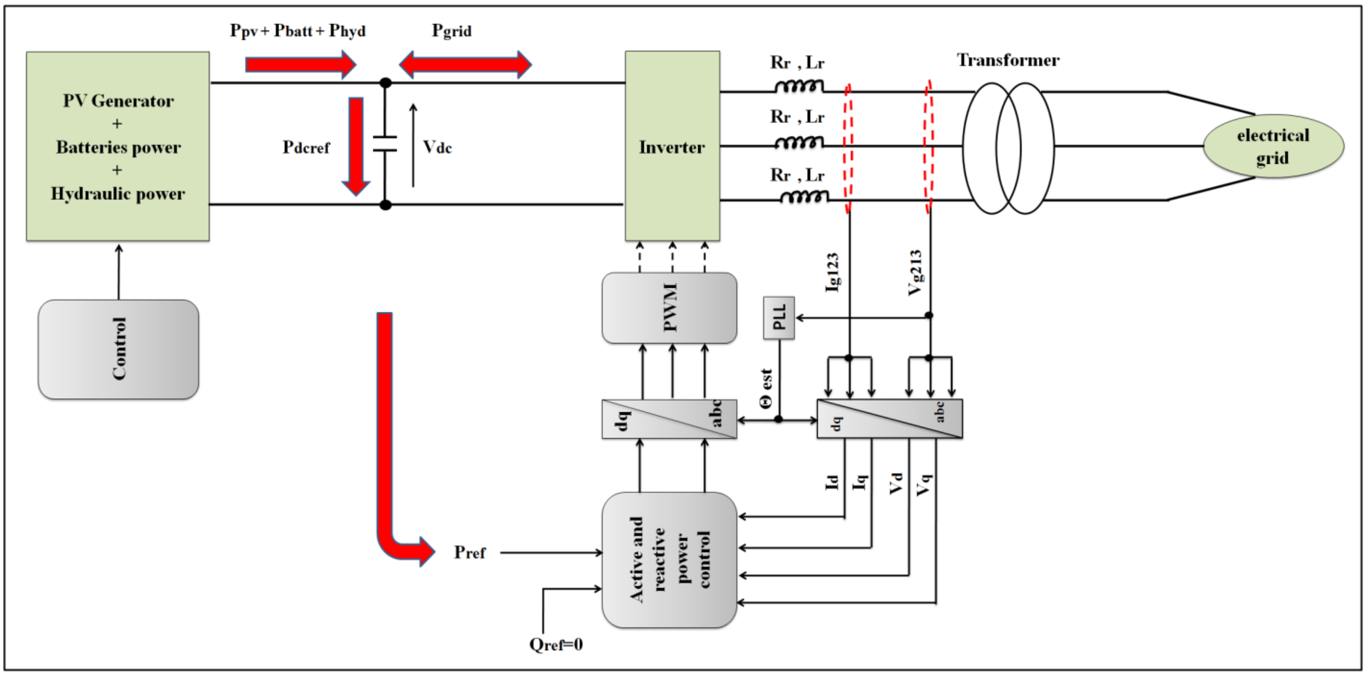


Fig. 12. Grid connected inverter control

When (Q =0), the voltages and currents are in the same phase, so unity power factor is achieved. Also, we can inject or recover the reactive power (Q_{ref} <0 or Q_{ref} >0).

The expression of the reference currents (I_{dref}, I_{qref}) depend to real grid voltages and the active and reactive reference power (P_{ref} , Q_{ref}) like demonstrated as follows:

$$\begin{cases} I_{dref} = \dfrac{P_{ref}V_{dg} - Q_{ref}V_{qg}}{V_{dg}^{\;2} + V_{qg}^{\;2}} \\ I_{qref} = \dfrac{P_{ref}V_{qg} - Q_{ref}V_{dg}}{V_{dg}^{\;2} + V_{qg}^{\;2}} \end{cases} \tag{20}$$

To manage the power flow in this system, we need to control the DC bus in any time [27, 28, 29, 30, 35, 36], "Fig.13" represent the capacitor voltage control used.

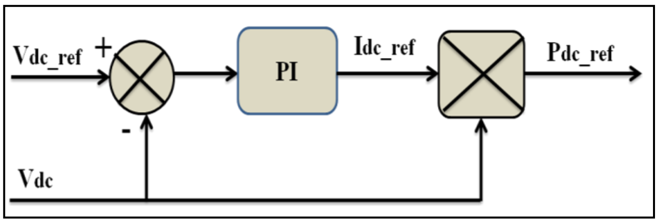


Fig. 13. DC control.

In DC bus, There are five power sources/consumers (PV, battery, pumping system, DC power, and the grid). For that, the reference power can be delivered to electrical grid is presented as follow "Fig.12":

$$P_{ref} = P_{pv} + P_{batt} + P_{hyd} - P_{dcref} \tag{21}$$

P_{pv} and P_{hyd} are a positive power values, but batteries power P_{batt} can be positive in charge mode or negative in discharge mode).

With:

P_{pv} : photovoltaic power
P_{batt} : battery power
P_{hyd} : hydraulic power.
P_{dcref} : DC bus power.

4. Simulation Results and Discussions

Several numeric simulations are accomplished in MATLAB/SIMULINK for evaluate our system in different conditions. "Table 1." shows the values of important element. The simulations tests are achieved in 1.5 s, for this, the globally modes operation are tested for prove the system behaviors.

Table 1. Parameters values

Elements	Values
Max PV power (W)	4600
Batteries voltage (V)	12*30
Motor-pump nominal power (W)	4000
Rotor speed (rpm)	1430
Nominal flow (m3/h)	10
Height (m)	10
Electric grid (V)	220/380

In this system, the DC voltage is fixed at 600V, with capacitance of 4400µF, "Fig.14" show that the DC voltage control proved to be robust with exchange between PV panels, storage system and electrical grid.

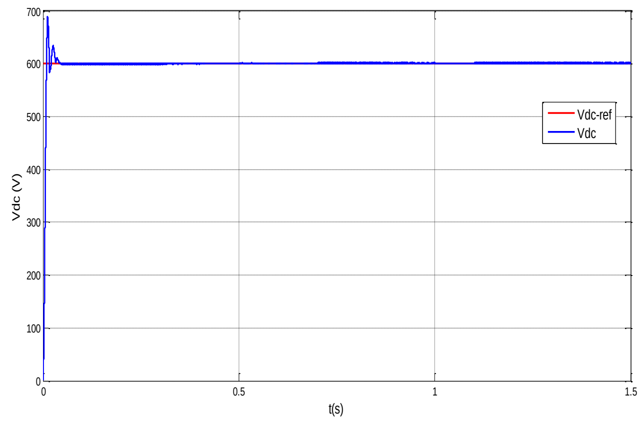
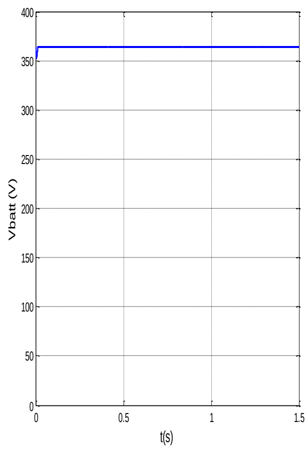
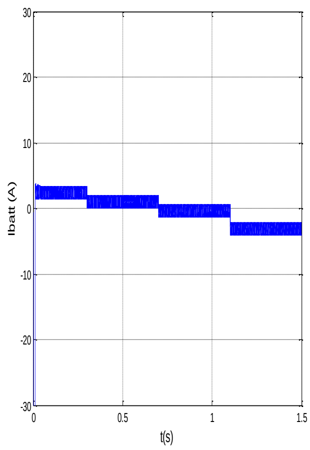


Fig. 14. DC Voltage regulation

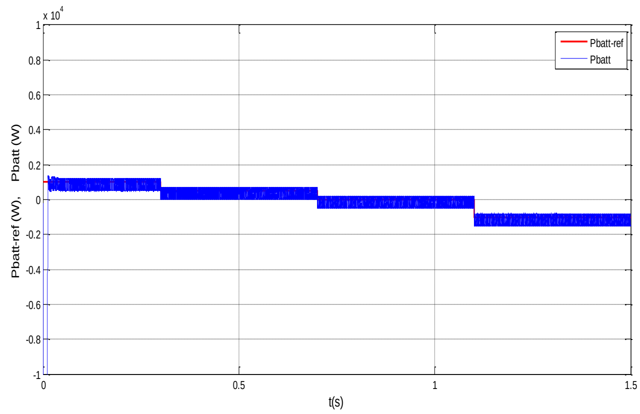
As indicated in “Fig.15” The control used manage the bateries power and current to the refernce imposed with verey good dydnamics, In other hand, the voltage is not infeluenced beacause the batteries has a long reponse time.



(a)



(b)



(c)

Fig. 15. Batteries characteristics

The pumping system on this study considered as a hydraulic storage used when we have a surplus PV power, for this, we can provision the farmer and agricultures by water in arid area. In other hand, both storage systems used can be alimented by electrical grid in necessary period (weak weather condition, night…), for that, the control strategy inverse the power flow direction.

Such as mentioned in “Fig.16-17-18-19” The reference power imposed to the pumping system produced a motor pump reference speed, so, for each values of this, we can regulate a fixed power flow, furthermore, the motor currents and torque follows their references. The pump hydraulic characteristics (flow rate, height), follow the vector control speed reference variations such as showing in “Fig.20”.

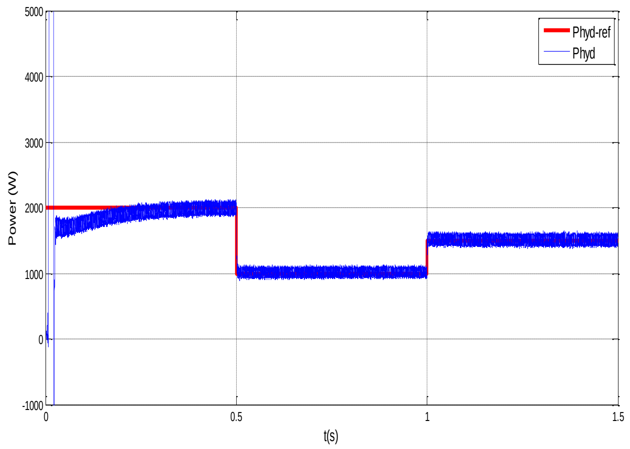


Fig. 16. refernece and real hydraulic power

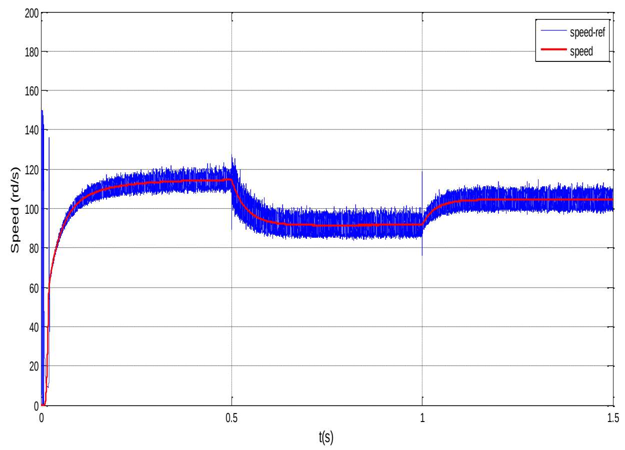


Fig. 17. pumped speed system

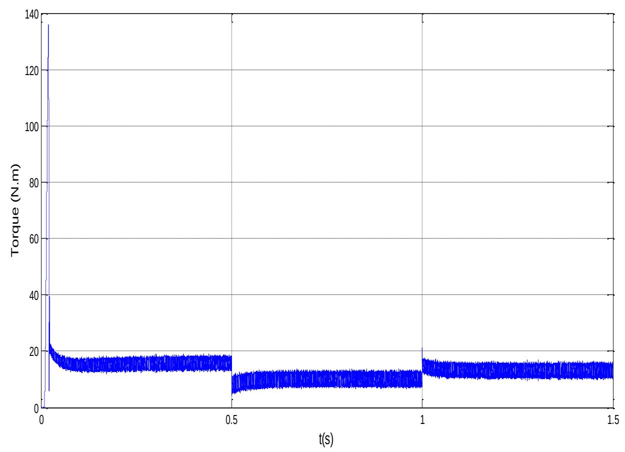


Fig. 18. motor torque for various power refernce

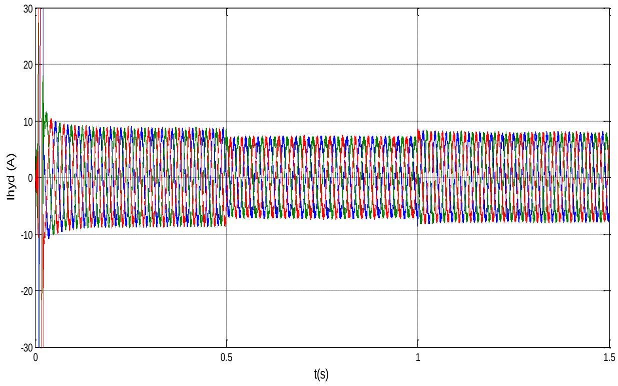


Fig. 19. absorbed motor currents for various power refernce

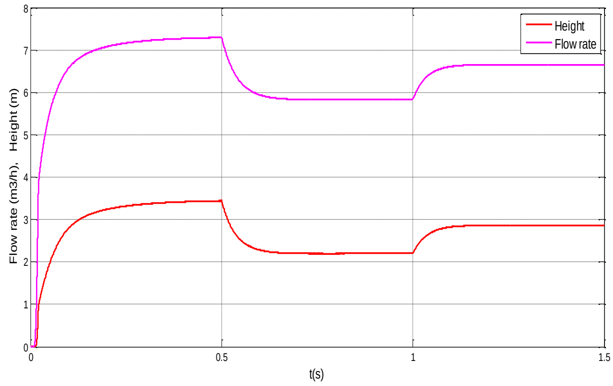


Fig. 20. centrifugal pump flow rate and height

The performance of the decoupled active and reactive power regulation for grid inverter is tested, for this, the behaviors of injected currents and powers are mentioned in "Fig.21-22-23"

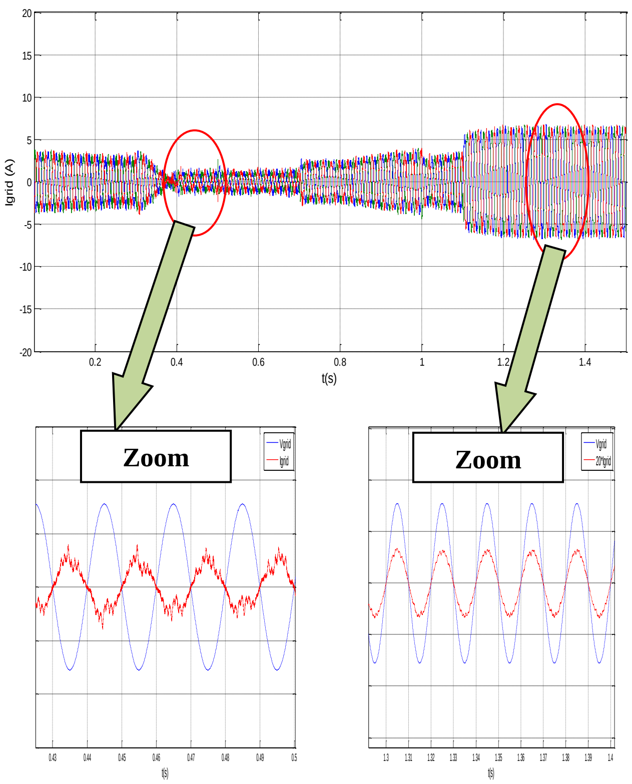


Fig. 21. Overall PV grid connected currents

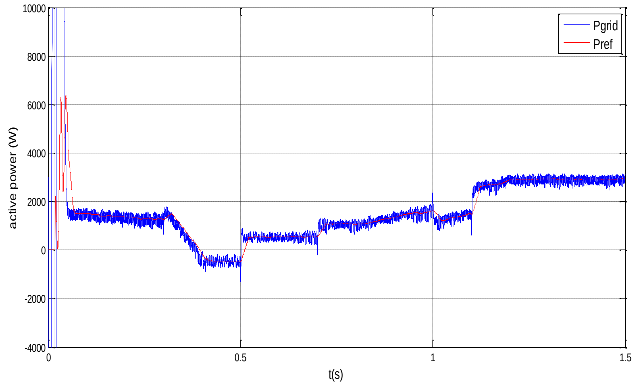


Fig. 22. Reference and active power variation

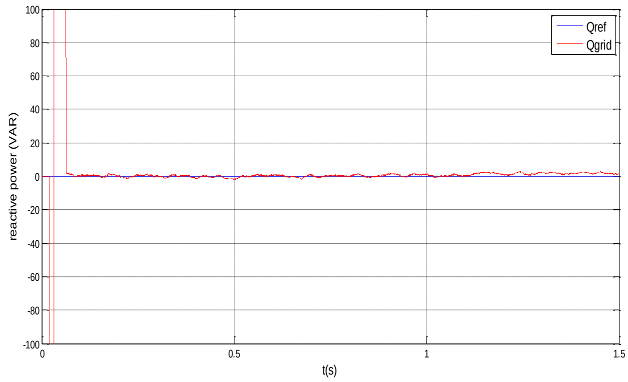


Fig. 23. Reference and reactive power variation

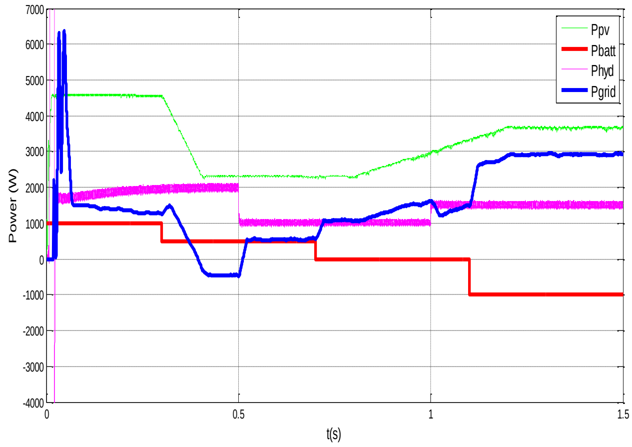


Fig. 24. Overall PV grid connected power flow

The overall photovoltaic grid connected system powers flows are presented in "Fig.24" in many several meaningful conditions can be produced in really case. Thus, Firstly with valuable illumination profile, the MPPT algorithm used present a good tracking performance in various illuminations values. The power flow efficiency is evaluated by the balanced energy system at the DC bus; we can observe small transit losses, also, the power flow evaluations demonstrate a high quality balance between batteries, pumping system and electrical grid.

The PV power produced is divided between batteries, pumped system and electrical grid, in other hand, if PV power is insufficient, the electrical grid can transfer the missed energy such as mentioned in “Fig.24” between 0.4s and 0.5s. Moreover, the grid currents form presented in “Fig.21” follow the active power level and they are in phase with the grid voltage (Q_{grid} =0), also, it can be in opposition phase if we are a reverse follow direction.

When the batteries are disconnected (P_{batt_ref}=0), more PV power excess can be transformed on hydraulic water for providing farmer in agriculture area. While the batteries are full charged, they can support electrical grid power like demonstrated in “Fig.24” between 1.2s and 1.5s.

5. Experimental Tests

To validate and evaluate the overall PV grid connected studied control system, we have focused in first time our work in inverter current control technique for regulating in d-q frame the instantaneous currents (I_{dinv}=C^{st}, I_{qinv}=0). The object is to prepare a platform that we can incorporate the active and reactive power control with batteries and pumping system. The simplified experimental bench system studied is shown in “Fig.25”, d-q current regulation is adopted and validated via PCI6052E card with matlab/simulink environment [20, 37].

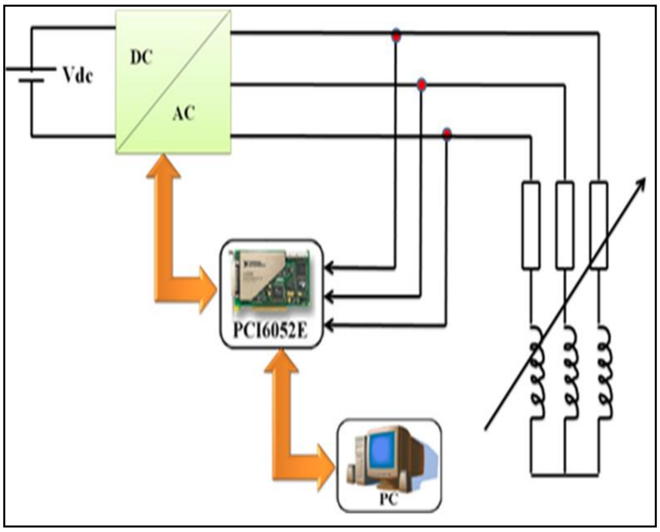


Fig. 25. Experimental test bench.

In this experience, we have used DC voltage V_{dc}=150V, the variable inductive load parameters are: (R=2.6Ω, L= variable), the switching frequency is f=2 KHz. The experimental results obtained are given in “Fig.26-27”:

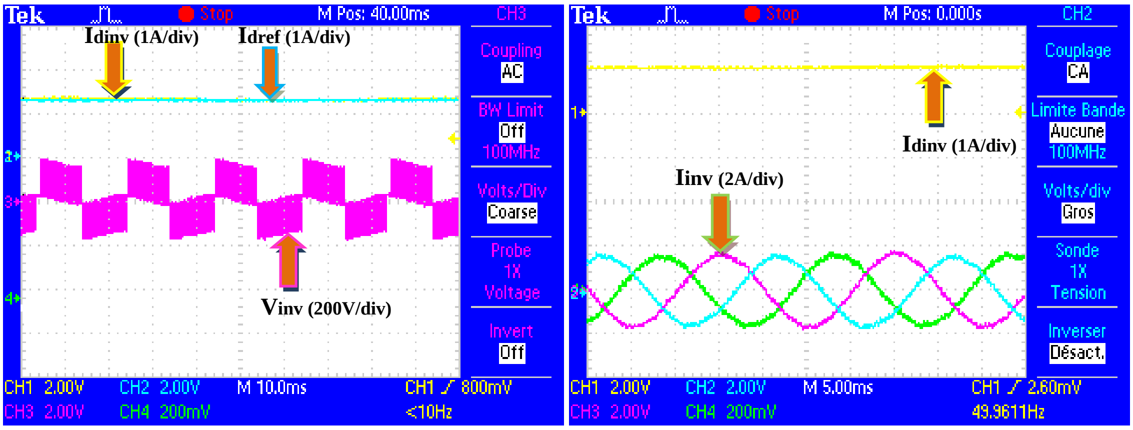


Fig. 26. instantanous inverter voltage and currents

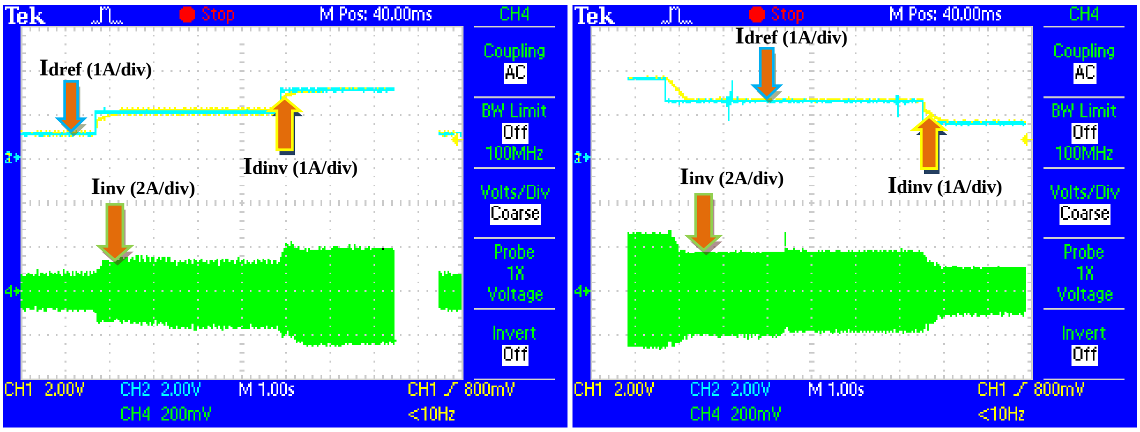


Fig. 27. Robustness d-axis regulation current

From the obtained results, we can observe that, d-q currents regulation adopted present a good performance in presence of a increasing or decreasing rapidly load variation, also, the inverter instantaneous currents follow perfectly all events. Furthermore, these results encourage us to complete the implantation and validation of this system in upcoming works.

6. Conclusion

Globally design of grid connected photovoltaic power installation assisted by batteries and water hydraulic pumping system has been studied and validated by noteworthy results in many rigorous situations. Perturb & Observe MPPT algorithm is adopted to pursue and extracted the available highest energy from sun in different situations. The injected power has been managed by a separately active and reactive power algorithm; thus, we can transmit the photovoltaic energy with unit power factor. Furthermore, the batteries are adopted and controlled to store or compensate the produced PV energy. For increasing the storage efficiency, when we have a higher PV production, water pumping system has been integrated in DC bus for providing agriculture and farmer by water. Many significant simulation and experiment results extracted from this study illustrate and prove the feasibility and reliability of this overall grid connected photovoltaic conversion system.

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