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ARTICLE

CONTRIBUTION OF ENERGY STORAGE IN IMPROVING THE INTEGRATION OF GRID-TIED PHOTOVOLTAIC SYSTEMS

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ABSTRACT

With the increased use of PV systems (PVSs) and the growth of their penetration level in the modern power systems, the effectiveness of grid-tied PV systems have become a spotlight topic for researchers in this field. As a contribution in the efforts aiming to improve the effectiveness of the PV systems integration to the electric grid, the objective of this paper is to investigate the performance of a grid-connected PV system that uses a bank of storage batteries. The battery storage system is integrated via a reversible chopper to perform the role of a buffer between the PVS and the point of coupling with the grid. A control method based on an optimal energy management approach (EMA) has been established to control the involved DC-DC and DC-AC converters. Furthermore, the contribution of the storage system has been discussed. Indeed, two study scenarios without and with the contribution of the storage system were considered and analyzed. Simulations under Matlab/Simulink® have been carried out to prove the performance of the proposed control method and the adopted power flow management. The found results prove the efficiency of the developed control strategy to ensure the connection of the hybrid system to the grid, while guaranteeing the power quality requirements.

KEY WORDS
Photovoltaic Systems; Storage Battery; Power quality; DC bus voltage regulation; Energy management

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INTRODUCTION

During last decades, fuel consumption and CO_2 emission increased due to the use of conventional power plants [1]. Serious attempts have been made to increase the energy self-sufficiency and meet CO_2 emission reduction target for both developed and in development countries [2], [3]. In this context, renewable energy sources have been included to ensure the energy security, the environmental sustainability and to play an essential role in future mix of energy policy [4]. Driven by relevant incentive policies, the grid-connected photovoltaic systems have been expanded widely due to the decreasing trend of capacity cost [5]. Thereby, PV energy harvesting systems have become the fastest growing renewable technology.

Grid-connected PV power systems can increase the proportion of solar energy on the power grid to reduce pollutant emissions, especially greenhouse gas (GHG) emissions, and global warming [6].

The major problems of PVGs are mainly around the following four levels [7-10]:

- The level of generation and the duty to extract, at any time, the maximum power available through the operation of commands based on techniques (MPPT) driving the DC-DC converters.
- The level of the DC-AC converter used to convert the direct current produced by the photovoltaic panels into alternating current adapted to the electrical network. Such an inverter plays a crucial role in solar energy production installations as it serves as a bridge between the photovoltaic system and the electricity grid, whether for a residential installation or a power plant.
- The level of synchronization and integration of photovoltaic and fluctuating energy in the electrical network.
- The level of the obligation to use a battery storage system in order to continuously ensure the availability of energy and to meet the demand for power demanded by the load.

By reason of the intermittent behavior of solar irradiation in nature, which is generally unpredictable, the production of energy from PV introduces more uncertainty in the operation of an autonomous microgrid integrating these generators [11]. The main challenge of using the sun as an energy source is that it may not be available when electricity is needed. Therefore, the incorporation of the energy storage system (ESS) allows the reduction of the uncertainty of the solar production is essential to improve the reliability and security of production. The ESS can play a key role in the energy generation and thus smoothing of the fluctuations in produced solar energy over a desired time horizon [12]. The ESS can also be used to offset the variations in load power.

Although the use of energy storage combined with a grid-connected PV system is still recent, there are already numerous configurations of integration of battery storage in solar generators. These configurations vary primarily based on functionality and application. The most distinctive topologies are AC voltage side coupling (AC systems) and DC voltage side coupling (DC systems) [13]. It is obvious that each of these topologies and its sub-variants has its particular advantages and disadvantages.

For the AC side coupling, the battery is coupled to the grid via an inverter. In general, this allows the storage system to be recharged from the grid other than the reinjection into the home network [14]. For this topology, the battery is installed and used independently of the PV system. If needed, these systems can also recharge the battery from the grid and not just from the PVS. Such systems may also be installed in homes where the PV system already exists but does not yet have storage or in case of extension of an existing storage system. This topology has some advantages namely the possibility of retrofitting an existing PV system, more flexibility and choice in the size of the systems and the modular possibility to increase it. Otherwise, its disadvantages revolve around the need for more space, the higher price because of the redundancy of the inverters (2 inverters required) and, in certain situations, the complexity of the calculating.

For the DC side coupling, the battery only stores solar energy while solar inverters are solely responsible for powering the grid. Some new photovoltaic inverters have been designed to also function as battery chargers. In this situation, the battery is charged by the DC side of the inverter. The connection of the PV-Battery system to the mains is ensured via the same inverter. Fewer elements are needed for the same functionality, which often gives cost and space advantages. In addition, the current generated by the PV system undergoes fewer conversion steps to the battery. In use, conversion losses are thus typically smaller. However, the actual losses will largely depend on the efficiency of the installed equipment. There is often a device to charge the battery by the grid during emergency [10]. This topology has advantages related to the savings in materials, thus reducing costs and the necessary space. In addition, if the battery is not charged by the network, the counting device is identical to that of a standard solar system. The main disadvantages are mostly related to the complexity of a possible extension of the system and the loss of flexibility due to the coordination of the PV- Battery sizing. Within the framework of self-sustaining autonomous energy systems, the feasibility assessment of hydrogen and battery storage device supporting a domestic PV system has been studied in [15]. The insufficiency of this work can be summed up to the fact that the dimensioning was limited to off-grid operation. Balint et al. have conducted a deep yearly comparison between various discharge methods of residential PV-Battery systems connected to the grid [16]. Though the found results are satisfactory for manufactures' BESS in terms of facilitating different system comparisons, other issues related to hybrid systems have not been investigated.

While considering the trade-off between various factors such as the storage health and the energy cost, an optimal planning of solar systems incorporating a battery bank was presented [17]. Furthermore, Asmae et al. approached a method of energy management for serving the load when the solar-battery system is connected to the grid [18].

In what follows, the material and methods section presents the basis of the modeling and the development of numerical models to be simulated, including those of the PVG and MPPT control, the storage system and its control and the inverter control. Afterwards, the results section focuses on the presentation and the discussion of the results of the developed simulations, dealing in particular with two scenarios i.e. without and with storage system. Finally, the conclusions and the future trends are given.

MATERIALS AND METHODS

The topology of the studied three-phase grid-connected PV system is illustrated in Figure 1. The scheme is based on a DC/DC boost converter which is in charge of both the MPP tracking of the PV generator and the generated power curtailment during grid voltage unbalances [19, 20]. In addition, a 2-level three-phase dc/ac stage ensures the connection to the grid via a LCL filter. The inverter is in charge of controlling the dc-link voltage control and the injecting of the generated power into the grid. Otherwise, the LCL filter is exploited to decrease the attenuation of the harmonics caused by the switching [20, 21].

This section focuses on the modeling and control of the whole system under study. Indeed, a first part was reserved for the modeling of the PV generator and the control of its step-up chopper via MPPT algorithm. A second part was focused on the study of the storage system and the control technique of the reversible chopper responsible for charging and discharging the battery bank. In addition, the third part was given to the control of the AC-AC converter on the grid side.

PVG Modelling and MPPT control

It is important to note that the modeling of the PVG was made by adopting the circuit with two diodes thanks to its accuracy compared to the model with two diodes [22]. By neglecting the characteristic resistances, the generated current is expressed as follows.

$$i_{PV}(G,T)=\frac{G}{G_n}\left[I_{scn}+K_i(T-T_n)\right]-\frac{I_{scn}+K_i(T-T_n)}{\exp\left(\frac{V_{ocn}+I_{scn}(T-T_n)}{nN_s k_B T/q}\right)-1}\cdot\left[\exp\left(\frac{v_{PV}}{nN_s k_B T/q}\right)-1\right] \quad (1)$$

where N_s is the number of PV cells connected in series to form the PV panel. T and G are the ambient temperature and irradiation, respectively. T_n and G_n are the temperature and irradiation at standard test conditions (STC), respectively. q is the charge of an electron, k_B is Boltzmann constant, n is the diode ideality factor. V_{ocn} and I_{scn} are the open circuit voltage (V_{oc}) and the cell's short circuit current (I_{sc}) at STC and k_v and k_i are the variation coefficients of the V_{oc} and the I_{sc}, respectively.

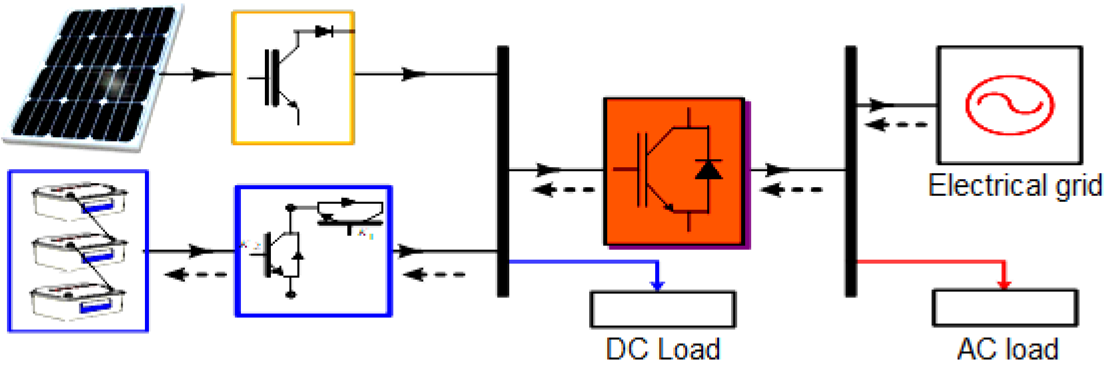

Fig. 1: Grid-connected PV-Battery hybrid system.

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To simulate the current and voltage, and therefore the power, of the PV generator containing N_{ss} panels associated in series and N_p panels connected in parallel, Eq. (1) is rewritten as in Eq. (2) and the power as in Eq. (3):

$$i_{PV}(G,T) = \frac{G}{G_n} N_p[I_{scn} + K_i(T - T_n)] - \frac{(I_{scn}+K_i(T-T_n))N_p}{\exp\left(\frac{(V_{ocn}+I_{scn}(T-T_n))N_{ss}}{nN_sN_{ss}k_BT/q}\right)-1} \cdot \left[\exp\left(\frac{v_{PV}}{nN_sN_{ss}k_BT/q}\right) - 1\right] \tag{2}$$

$$P_{PV}(G,T) = i_{PV}(G,T).\, v_{PV}(G,T) \tag{3}$$

In order to locate the MPP, it is essential to express the power derivative with regard to the generator voltage to obtain the following new characteristic function:

$$P_{PV}(G,T,v_{PV}) = \left\{\frac{G}{G_n} N_p[I_{scn} + K_i(T - T_n)] - \frac{(I_{scn}+K_i(T-T_n))N_p}{\exp\left(\frac{(V_{ocn}+I_{scn}(T-T_n))N_{ss}}{nN_sN_{ss}k_BT/q}\right)-1} \cdot \left[\exp\left(\frac{v_{PV}}{nN_sN_{ss}k_BT/q}\right) - 1\right]\right\} \times v_{PV}(G,T)$$

(4)

With a view to identify the combination of temperature and irradiance allowing to extract the maximum power point tracking (MPPT) via incremental conductance (IC) MPPT technique, the power derivative is calculated. After determining the voltage value which corresponds to the maximum power, the duty cycle of the PVG side DC/DC chopper is adjusted.

The MPPT controller is designed to overcome the constraints generated by climatic conditions which are constantly in continuous and even rapid changes [7]. The performance of this controller depends essentially on the robustness of this controller in the face of sudden atmospheric changes and in particular on the speed of reaching the MPP and on the way of oscillating nearby it. In this paper, an Improved Incremental Conductance (IIC) MPPT algorithm controls the PV side boost converter [5].

Storage system modelling and control

In a PV installation, the storage corresponds to the conservation of the PVG energy, waiting for later use. The management of solar energy requires considering storage according to weather conditions. In a general way, the storage of electrical energy passes through a form of intermediate energy (such as electromagnetic, kinetic, thermal, gravity, compression, electrostatic, electrochemical ...) convertible into electricity. According to the bibliography, there are two types of storage to consider: short-term storage (less than 10 minutes) and long-term storage (more than 10 minutes) [12-14]. The selection of the appropriate storage system is founded on mass power, mass energy, number of operating cycles, cost and energy efficiency.

Generally, the storage size is determined by the period of time over which the batteries are able to cover the average consumption without the participation of any other power source. When sizing a storage battery bank, limitations in both charge and in discharges rates have to be considered [5]. Knowing that the energy amount which can be drawn from a battery storage is determined by the ratio of discharge power to storage capacity. As declared above, the nominal battery storage capacity cannot directly be linked to the storage size.

In this work, the choice has been oriented towards Lithium-Ion batteries. This choice was justified by the efficiency that exceeds 95%, the extremely high energy density and the high power density of this type of battery. This is due to the lightness of the used electrolyte.

The purpose of the storage system is to ensure a production permanence whether for an electricity grid or a load and to absorb peaks of consumption to avoid energy imbalances. After having selected the appropriate storage mode, has such an application, the solicitations on the latter are not the same, and it is appropriate to adapt the sizing of the system subject to study depending on the intended purpose application. For our stationary application, the load profiles are rather energetic because of the needs and the energy availability over time. Thevenin's model of the battery is shown in Figure 2.

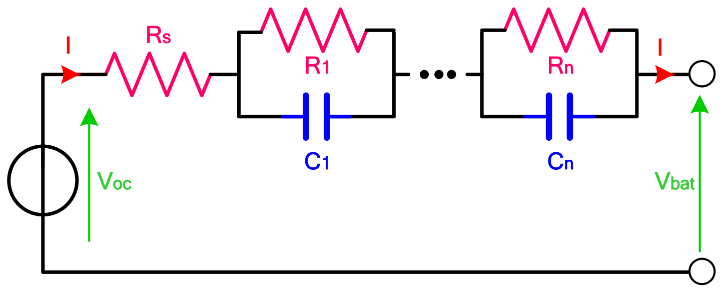

Fig. 2: N-Order battery Thevenin model.

The battery voltage V_{bat} (t) is given by:

$$V_{bat}(t) = V_{oc}(SoC(t)) - u_s(t) - \sum_{i=1}^{n} u_i(t) \quad (5)$$

$V_{oc}(SoC(t))$: Open circuit voltage changing according to the state of charge,

$u_s(t)$: Voltage drop across the terminals of Rs,

$u_i(t)$: Voltage drop across the terminals of the ith *R//C* circuit.

In the literature, mainly three types of models can represent the temporal behavior of the battery: equivalent electric circuit type models, electrochemical models and black box type models (using fuzzy logic or neural networks) [13, 14]. The model that best fits our needs for the current study is shown in Figure 2. This choice was imposed by the fact that:

- the model needed aims to simulate the battery dynamic temporal behavior at low frequencies (<= 1 Hz) and the high frequency components have been neglected
- the model with *R//C* circuits can be easily applied to different batteries.
- based on Thévenin's models, the expression of each time constant (R_i; C_i) of the *R//C* circuits in series is more explicit than the transmission circuits
- the complexity of the model can be easily calibrated by modifying the number of circuits *R//C*.

In the same context, temporal characterization is chosen because:

- the temporal data are more suitable for studying the problem of relaxation with respect to frequency data.
- with the proposed structure, the battery model can be characterized only with temporal data, which avoids the use of specific equipment (impedance spectrometer).
- the battery model can be characterized even for high currents.

Given the fluctuating nature of the power generated by the PV generator, which depends primarily on meteorological conditions of irradiance and temperature, it is of utmost importance to integrate a charge regulator to block reverse charge of the PVG and protect the bank of battery against overcharging and rapid discharge. Also, the use of a bidirectional converter is imposed to ensure a secure connection of the loads of different types (DC and AC) [10]. To ensure the required efficiency and reliability, the proper choice of the converter rating is dependent on knowing the correct peak load demand on the battery and the load simultaneously.

Furthermore, it is important to note that on an industrial scale, the majority of bidirectional converters sold on the market integrate the battery charge controller.

DC-AC converter control

The mains side converter mainly deals with the conversion of direct voltage into three-phase alternating voltages. This bidirectional current inverter is made up of three switching cells, each one made up of two

IGBT transistors which are connected to two diodes in anti-parallel and controlled by PWM modulation. It is very important to mention that a DSOGI-based PLL has been adopted for the DC/DC inverter [23].

The DC / AC stage control method relies on cascade control using an internal current loop and an external voltage loop [24]. Also, the square of the DC bus voltage was controlled by a PI-based control technique according to [5]:

$$V_{dc} = \sqrt{\frac{2}{C_{dc}} \cdot \int (P_{PV} + P_{SB} - P_g^*).dt} \qquad (6)$$

RESULTS

Before presenting and discussing the simulation results, it is important to recall that many criteria have been taken into account to maximize the efficiency of the studied PV-Batteries system connected to the grid. Firstly, a great importance was paid on extracting the maximum power available from the GPV side. Indeed, in the simulated scenario, the considered sunshine and temperature profiles are those presented in figure 3 (a) and (b), respectively. Under these conditions, the optimum power generated by the PVG is depicted in figure 3 (c).

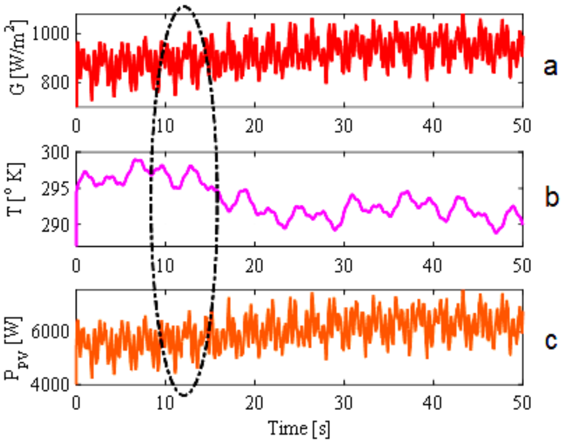

Fig. 3: Weather conditions and PVG power.

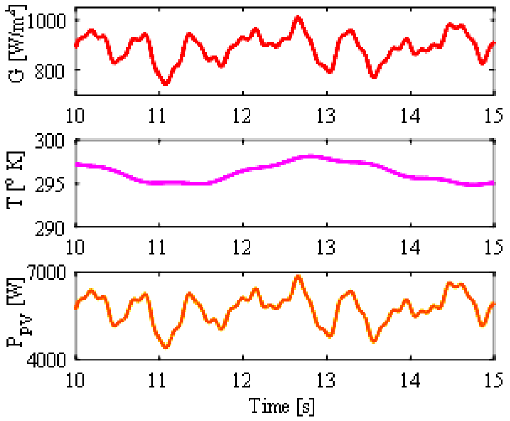

Fig. 4: Zoom version of Fig. 3.

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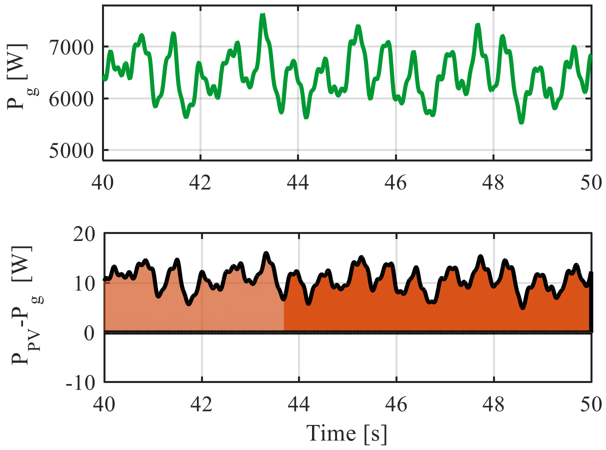
First scenario: without storage system contribution

The first scenario consists of disconnecting the storage system. In this case all of the PVG power is injected into the PCC without the contribution of the storage system.

The power P_{PV} generated by the PVG is completely transmitted to the grid (P_g) while keeping the DC bus voltage constant. This is very clear in Figure 5 showing the shape of the power (P_g) transmitted to the point PCC and the gap between the power P_{PV} and P_g which does not exceed 15 W reflecting the losses.



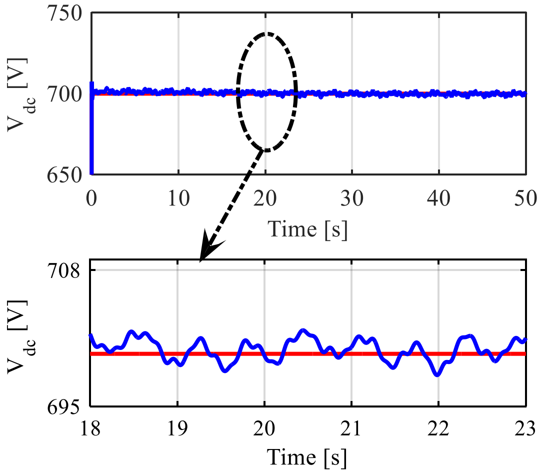


Fig. 5: Active power exchanged with the grid and power losses. **Fig. 6:** DC bus voltage and its reference value.

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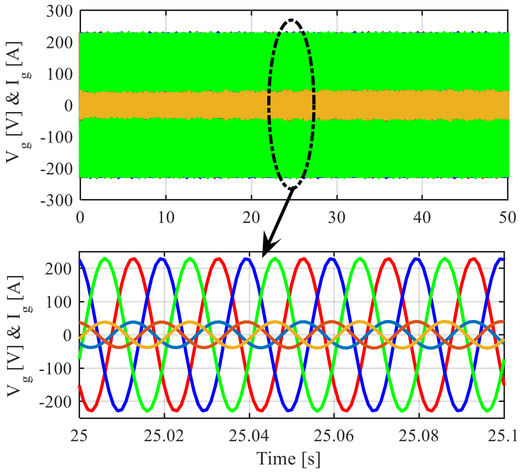
Under the same situations, the waveform of the voltage at the DC bus level is depicted in Figure 6. It is clear that the technique of controlling the voltage of the DC bus manages to keep its value close to its reference value as depicted in the zoomed Figure 6.

With regard to the electrical quantities exchanged with the electrical network, great importance has been given to the nature of the currents injected at the PCC point and that of the voltages at the same point. The following figure (Fig. 7) shows that both the voltages are sinusoidal. Otherwise, the currents are also sinusoidal albeit their amplitude is fluctuating because it depends on the fluctuating PV generator power P_{PV} which confirms that the proposed control system is effective.



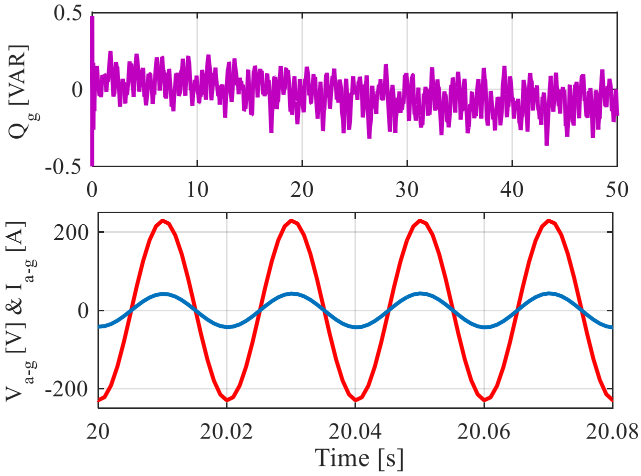


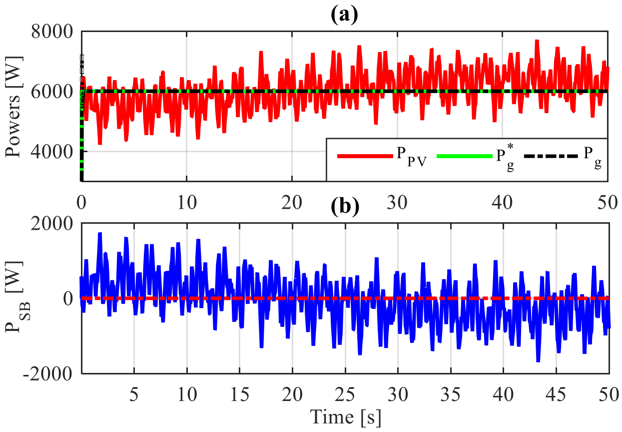
Fig. 7: Grid voltages and currents. **Fig. 8:** Reactive power and phase shift between voltages and currents at the PCC point.

Moreover, the grid reactive power is simulated in figure 8. Depending on the P_g power transmitted via the DC bus to the power grid, the reactive power is zero although negligible fluctuations are registered. In this same context, the nullity of reactive power is clearly shown by the fact that the voltage and the current of the same phase are perfectly in phase as shown in the same figure 8.

The second scenario deals with the case where the power to be injected into the network/even into the AC loads is constant (6 kW). In this case, all of the fluctuating PV power is used either to charge the storage batteries or to be fed into the PCC. This means that the storage system acts as a buffer between the PV generator and the PCC point where a constant reference grid power (P_g*) should be maintained.

Second scenario: with storage system contribution

For this second scenario, the simulations results are also convincing. Indeed, figure 9 (a) clearly shows the success of the proposed control strategy to ensure the complementarity between the PVG and the adopted BSS and to achieve that the power injected into the grid P_g is equal to its imposed constant reference.



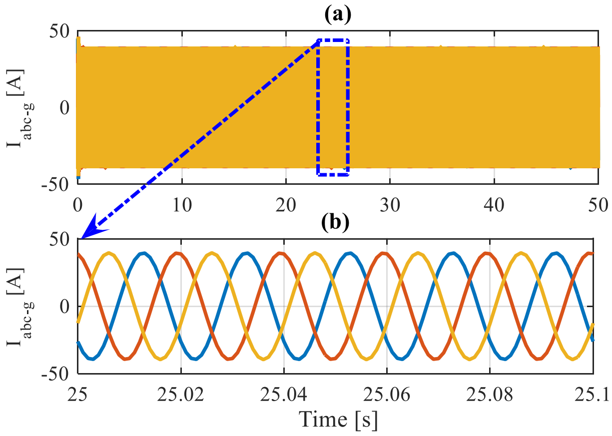


Fig. 9: Active power exchanged between the GPV, the storage system and the grid. **Fig. 10:** Grid currents waveforms.

Figure 9 (b) shows the behavior of the power exchanged between the battery storage (P_{SB}) and the DC bus. The principle of the proposed command is clearly proven. This principle consists in the fact that if the power of the GPV (P_{PV}) is greater than that of the grid (P_g), the excess is injected to charge the storage batteries. Otherwise, the lack is compensated by discharging the batteries to meet the power requirements of the PCC point (P_g*).

Still on the grid side, the waveforms of the currents injected at the PCC point are shown in figure 10. It is clear that these currents are sinusoidal and have constant amplitude.

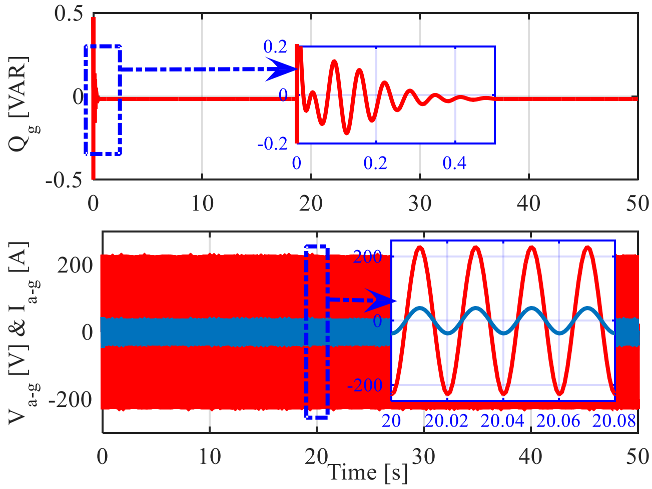


Fig. 11: Grid reactive power and grid voltage and currents.

In order to get an idea of the behavior of reactive power, figure 11 shows its zero value and its temporal evolution. Moreover, in the same figure, it is shown that the currents and voltages are in phase.
Comparative Analysis

After presenting and discussing the found simulation results, the Table 1 summarizes a brief comparative analysis. The comparative study has been based on the literature on the PV-storage systems principle. The comparison lies on the studied system configuration, its location, its On-grid or Off-grid connection, the used storage system, the type of involved battery, the main goal of the study, the adoption of an energy management approach and finally the consideration of high frequency control of power electronics converters. The conducted comparative study distinguishes the present work from the previously appeared. One can conclude that the proposed research is advantageous as it takes into account the issues of power quality and so avoids disturbing the electric grid.

Table 1: Comparative analysis

Studied System	Location	On-grid or Off-grid	Storage system	Battery type	Main objective	Energy management	High frequency converters control	Ref
Solar PV system	Finland	Off-grid	Battery + fuel cell	Lithium-ion	Technical feasibility of off-grid residential single-family house	Yes	No	[15]
Residential PV systems	Hungary	On-grid	Battery	Lithium-iron-phosphate	Comparison of different residential self-consumption-reducing discharge strategies	No	No	[16]
residential photovoltaic generation	India	On-grid	Battery	Lead acid	Increasing the profitability of a grid connected PV-Battery system	Yes	No	[17]
PV-battery residential installation	Morocco	On-grid	Battery	Not specified	Enabling the connection or the disconnection from the grid to manage its excess/lack of energy	Yes	No	[18]
PV-battery system	KSA	On-grid	Battery	Lithium-Ion	Enhancement of the PV-Battery system's ability to supply a clean and stable power flow	Yes	Yes	Our

CONCLUSIONS

This paper focuses on the piloting of a grid-connected PV system equipped with battery storage. The control system relies on different points, namely the MPPT algorithm applied to the DC/DC chopper on the

GPV side, the control of the reversible DC/DC converter controlling the charging in addition to the discharging of the battery storage system, the energy management algorithm and finally the control of the different currents and voltages of the DC/AC grid side converter to guarantee a perfect connection of the system to the PCC point. The simulations were developed using MATLAB software. The results of the simulations confirm that the presented approaches are efficient and effective for a better exploitation of the photovoltaic systems. Although the results of the simulations show satisfactory performances of the proposed method for the control of the hybrid PVG-BESS system connected to a balanced grid, such performances will be degraded since the occurrence of a voltage fault on the grid side. The investigation of the efficiency of the proposed strategy and its improvement during unbalanced grid conditions is a subject to be treated as future studies.

CONFLICT OF INTEREST

The authors certify that they have no conflict of interest.

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None.

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