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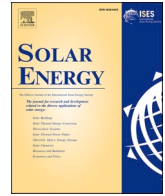


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Limits control and energy saturation management for DC bus regulation in photovoltaic systems with battery storage

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ABSTRACT

Because of the considerable fluctuations of the power generation and load in Photovoltaic (PV) - Battery (BAT) systems, power management strategies become indispensable since BAT is needed to maintain the generation/load balance, and to regulate the DC bus. Indeed, energy management strategies must take into account the limits of the system, i.e. the nominal PV/BAT power rating and the state of charge (SOC) of BAT. However, the actual use might be different from the intended one, forcing the system to attain its limits. This paper is mainly focused on the limits control and energy saturation management applying to a sample standalone DC micro grid. It consists to share accurately the variable power loads among sources according to their ratings, including the regenerative braking in minimum SOC^{BAT} case and the full supply of power load demand in maximum SOC^{BAT} case. Furthermore, the DC bus voltage is regulated to its predefined level, as a design parameter.

The proposed control algorithms are detailed, and the system design during overstress and nominal conditions is given. The main advantage of this algorithm is its simplicity. The efficiency of the control strategy for energy saturation management is verified and analyzed through simulation/experimental system using Matlab/Simulink and DSpace. The results obtained show that the proposed technique can intelligently manage the energy flows and thus ensure that the system operates correctly and safely in the different modes: normal mode and saturated mode.

1. Introduction

The current situation of world energy consumption, with a continuous increase in energy demand as well as the environmental pollution associated with harmful gas emissions and the exhaustion of fossil fuel reserves ([IEA]–International Energy Agency, 2018), has encouraged the use of renewable energy sources in association with other sources for distributed generation. This association refers to hybrid systems that are composed of one or more renewable energy sources and energy storage systems. BAT banks permit adapting the intermittent power provided by the renewable sources to load demanded power. This hybrid systems can be classified according to their operation in stand-alone or grid-connected mode. An autonomous microgrid can be seen in remote rural areas and in the use of equipment that needs energy autonomy for their operation in automotive as plug-in chargers for electrical vehicles,

in avionic space vehicles or other or marine industries and sea vehicles (Hirsch et al., 2018).

The large-scale systems cited above are attractive, but before they can be achieved, it will be crucial to overcome certain restraints by optimizing the total operation of a hybrid PV-BAT system. Thus, by going back to a smaller scale, and exploring a stand-alone generation system it will be necessary to surmount the three commonly recognized problems concerning DC bus control/stabilization, power balancing, and BAT management, that are more challenging in PV-BAT hybrid systems due to the intermittent nature of PV energy source, and which result in the need for more advanced algorithms of control and power management strategies. The stability of the PV-BAT DC hybrid systems is evaluated based on the stability of its DC-bus level (Ajai et al., 2011; Chen and Xu, 2012), this being one of the principal control objectives (Bhayo et al., 2019). On the other hand, BAT systems are limited due to a number of functioning restraints, as explicated further in this section.

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Nomenclature

<i>PV</i>	photovoltaic
<i>BAT</i>	battery
<i>MPPT</i>	maximum power point tracking
<i>PLT</i>	power load tracking
<i>PWM</i>	pulse-width modulation
P_{pv}	the photovoltaic power, W
P_{BAT}	the battery power, W
P_{Load}	The power load demand, W
η_{PV}	PV power converter efficiency, %
η_{BAT}	battery power converter efficiency, %
η_{Load}	load power converter efficiency, %
<i>SOC</i>	state of charge, %
SOC_{max}	maximum state of charge, %
SOC_{min}	minimum state of charge, %
V_{BUS}	DC bus voltage, V

$I_{sources}$	The sources current, A
V_{BAT}	batteries voltage, V
I_{BAT}	batteries current, A
V_{PV}	PV modules voltage, V
I_{PV}	PV modules current, A
I_{Load}	load current, A
I_{D-Load}	dump laod current, A
$V_{BUS-ref}$	DC bus voltage reference, V
$V_{BAT-ref}$	batteries voltage reference, V
$I_{BAT-ref}$	batteries current reference, A
V_{PV-ref}	PV voltage reference, V
I_{PV-ref}	PV current reference, A
$V_{BAT-max}$	maximum BAT voltage, V
$I_{BAT-max}$	maximum BAT current, A
$I_{BAT-min}$	minimum BAT current, A
V_{PV-max}	maximum PV voltage, V
I_{PV-max}	maximum PV current, A

Regarding DC-bus regulation and energy management strategies for DC hybrid systems, many researchers have conducted advanced studies on modeling, optimal operation, optimum size, advanced controller design and optimal management of hybrid power systems (Uzunoglu et al., 2009; Ghazvini and Olamaei, 2019; Sichilalu et al., 2015; Erdinc et al., 2012; Bigdeli, 2015; Li and Qiu, 2016; Mahmood et al., 2015; Choudar et al., 2015; Tummuru et al., 2015; Maleki et al., 2015; Mohanty et al., 2016; Ren et al., 2016). The DC-DC converter connected to the PV panels is controlled using algorithms of tracking the maximum power point (MPPT). The energy storage system connected to the DC-bus link, is controlled through bidirectional converter in order to regulate the DC-bus level then to ensure the overall balance of the system in case of surplus or insufficiency of power (Bernasconi et al., 1861; Ramos-Paja et al., 1847). However, more constraints must be envisaged: power limitation generated by the PV system (Lu and Wan, 2016; Kumar et al., 2015; Sechilariu et al., 2014), when the BAT attains the maximum of SOC in case of low power load, or disconnection of load when the BAT attains the minimum SOC in case of high power load (Lu and Wan, 2016; Kwasinski and Onwuchekwa, 2011). In Balog et al. (2012) and Alramlawi et al. (2018) load shedding approaches are proposed for the cases when power generation sources are insufficient. Similarly, Cho and Valenzuela (2019), Matrawy et al. (2015), Olatomiwa et al. (2016) used load shedding method to prevent the BAT from falling below the minimum SOC only in the case where critical loads are not present. However, it necessitates an over-dimensioning of the PV system and the BAT when critical loads are connected to the PV system. On the other hand, Refs Liu et al. (2011), Kanchev et al. (2011), Ghoddami et al. (2012), propose renewable power generation curtailment strategies for the case in which BAT cannot absorb the surplus of power. These restrict the rate charging of BAT through the full absorption power; though, BAT maximum charging current should at the same time be limited. Moreover, the power of each source is not curtail proportionally to its nominal rate. Xu and Chen (2011) restricts the BAT maximum absorption power to prevent the BAT from exceeding the maximum SOC. However, since BAT operates as nonlinear load during the charge mode, they do not guarantee that the charging currents are limited. Alternatively, Liu et al. (2011) limits the maximum SOC that results in unusable capacities.

In contrast of the approaches proposed in literature wherein renewable energy sources permanently work with their MPPT mode, the control algorithm considers only two operating modes: charge and discharge for the BAT, this paper proposes new mechanisms of control for the PV-BAT hybrid system in over-stressing conditions, system limitations and saturation mode. Limits control and energy saturation management must be included in the control strategy to guarantee safe and efficient use of the system. The control proposed for the

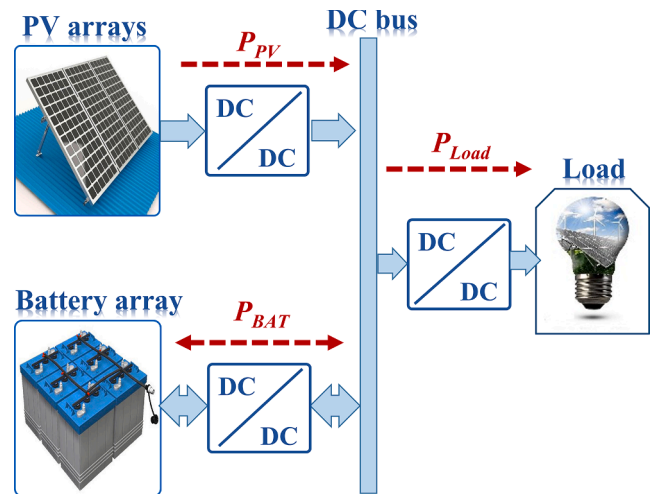


Fig. 1. The conventionnel parallel architecture for hybrid PV-BAT systems.

implementation of the system limits management ensures the originality of this approach, and guarantees continuity of service and safe operation.

The contribution of this paper focuses on limits control and energy saturation management for the operation of the PV-BAT hybrid system, includes the following: 1) the proposed energy saturation management strategy uses PV generators as controllable source and limits its power if necessary. Two modes of operation are used in PV system: MPPT and power load tracking (PLT) (Wang et al., 2013). Simultaneously controls charging/discharging current of BAT. The absorbed power is measured on dynamic basis in real time in function of PV power and service availability constraints. 3) The proposed strategy includes a dissipation system connected to the DC-bus in parallel with loads. Its function is to allow the smooth transition in changing modes of operation when the system reaches its upper (high SOC BAT) or lower limits (low SOC BAT). 4) Controller-In-Loop simulations and experimentation are carried out using MATLAB/Simulink and real-time dSPACE controller board to validate the proposed controls.

This paper is structured as follows: the hybrid PV-BAT power source architecture for stand-alone applications is presented in Section 2. Section 3 details the design of a real time limits control and saturation management of power. Section 4 presents and discusses the obtained results under variations of environmental conditions in operating and

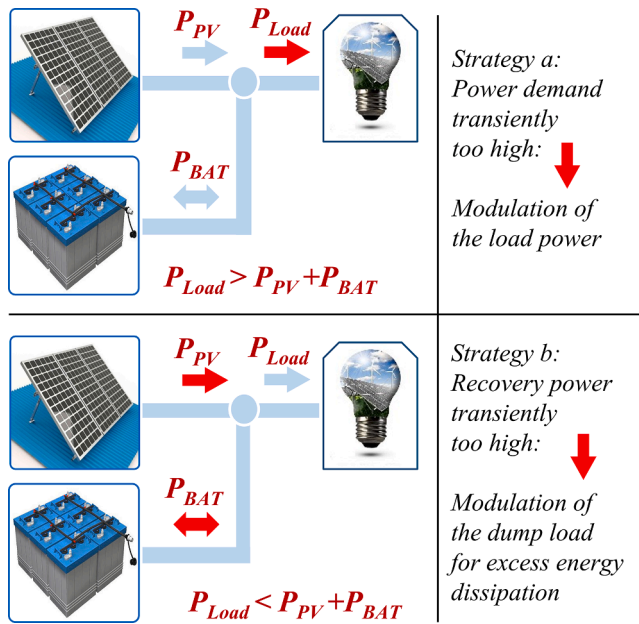


Fig. 2. Strategies for restricted power availability.

limits conditions of load demand and BAT. Finally, the conclusion of the paper is given in Section 5.

2. Case study and problem definition

2.1. System structure

The PV-BAT hybrid system architecture, based on commonly used in several applications, can be designed by the technology of DC micro grid (Jin et al., Aug. 2014). It is principally formed by a PV system, a BAT system and a load system. The PV system consists of PV arrays connected to DC bus through DC/DC converter. The BAT system is composed of BAT array connected to the DC bus through bi-directional DC/DC converter as shown in Fig. 1.

Eq. (1) gives the overall power balance of the PV-BAT hybrid system, where P_{PV} represents the power generated by the PV system, P_{BAT} the power supplied or stored by the BAT system, and P_{Load} is the power load demand. The power sources is positive and the demanded power load is negative. Therefore, the equation for keeping the balance of power in the DC bus must always be respected:

$$\eta_{Load}P_{Load}(t) = \eta_{PV}P_{PV}(t) + \eta_{BAT}P_{BAT}(t), [36]. \quad (1)$$

where η_{PV} , η_{BAT} and η_{Load} are the power converter efficiencies linked to the PV generator, battery system and load respectively. In this work, we assumed the value of the converter efficiency set around an average of 85%.

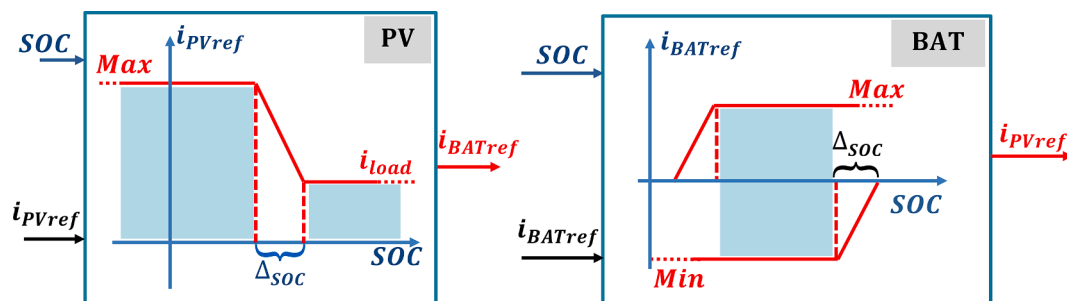


Fig. 3. PV-BAT current limits control in saturated mode.

2.2. Problem definition

With regard to the proportional availability of energy sources in relation to the ratio of demand within isolated DC PV-BAT hybrid systems, three scenarios are considered: 1) power of sources and loads are balanced; 2) power loads is higher than power sources resulting in a drop in DC bus voltage when any load shedding is applied; and 3) power sources exceed load demand cause BAT overcharge and DC bus voltage rise. This paper focuses on cases 2) and 3) where the power load demand shedding should be applied and PV power curtailed if they reach the BAT charging/discharging rates (Fig. 2).

The control algorithm should consider that BAT has two SOC limits: upper limit in maximum state of charge (SOC_{Max}) when it is fully charged, and lower limit in minimum state of charge (SOC_{Min}) when it is fully discharged. If the BAT works over these limits, its lifetime can be considerably shortened (Kucevic et al., 2020; Najafi, 2020; Zhao et al., 2013). Consequently, control strategy should incorporate two modes of operation: (1) limiting the PV power so that it equal to the power demanded by the load ($P_{PV} \approx P_{Load}$), when SOC_{Max} is reached; and (2) shedding the power load which is needed when SOC_{Min} is attained. The PV generator must be functioned with MPPT till the BAT attains an allowable SOC level to resupply the full load demand (Wang et al., 2013).

3. Limits control and saturation management

3.1. Local sources limits control

A series of phenomena have been identified that affect the functioning of BAT during charging and discharging modes noted that BATs are current-limited and also voltage-limited. Indeed, exceeding their nominal voltage leads to rapid deterioration at low efficiency due to a high and insignificant present power (Oliveira et al., 2016): 1) Using high charging/discharging currents leads BAT voltages to quickly attains its gassing threshold; 2) power losses, through its internal resistance and thermal effects, rise with elevated SOC rates; 3) BAT couldn't be charged/ discharged with a steady elevated charging/discharging currents respectively (Jing et al., 2019).

$$-V_{BAT_min} \leq V_{BAT_ref} \leq +V_{BAT_max} [41]. \quad (2)$$

Also, the currents of each source are delimited as follows:

$$\begin{cases} 0 \leq i_{PV} \leq i_{PVmax} \\ i_{BATmin} \leq i_{BAT} \leq i_{BATmax} \end{cases} [41]. \quad (3)$$

The limits control strategy consists in gradually changing the PV and BATs current reference when the value of SOC reaches one of its upper or lower limits (Fig. 3):

Indeed, the protection of each source is ensured by a local protection system based on dynamic current imitations (Eqs. (4), (5) and (6)):

- i_{BATmax} is gradually set to zero when SOC approaches SOC_{Min} :

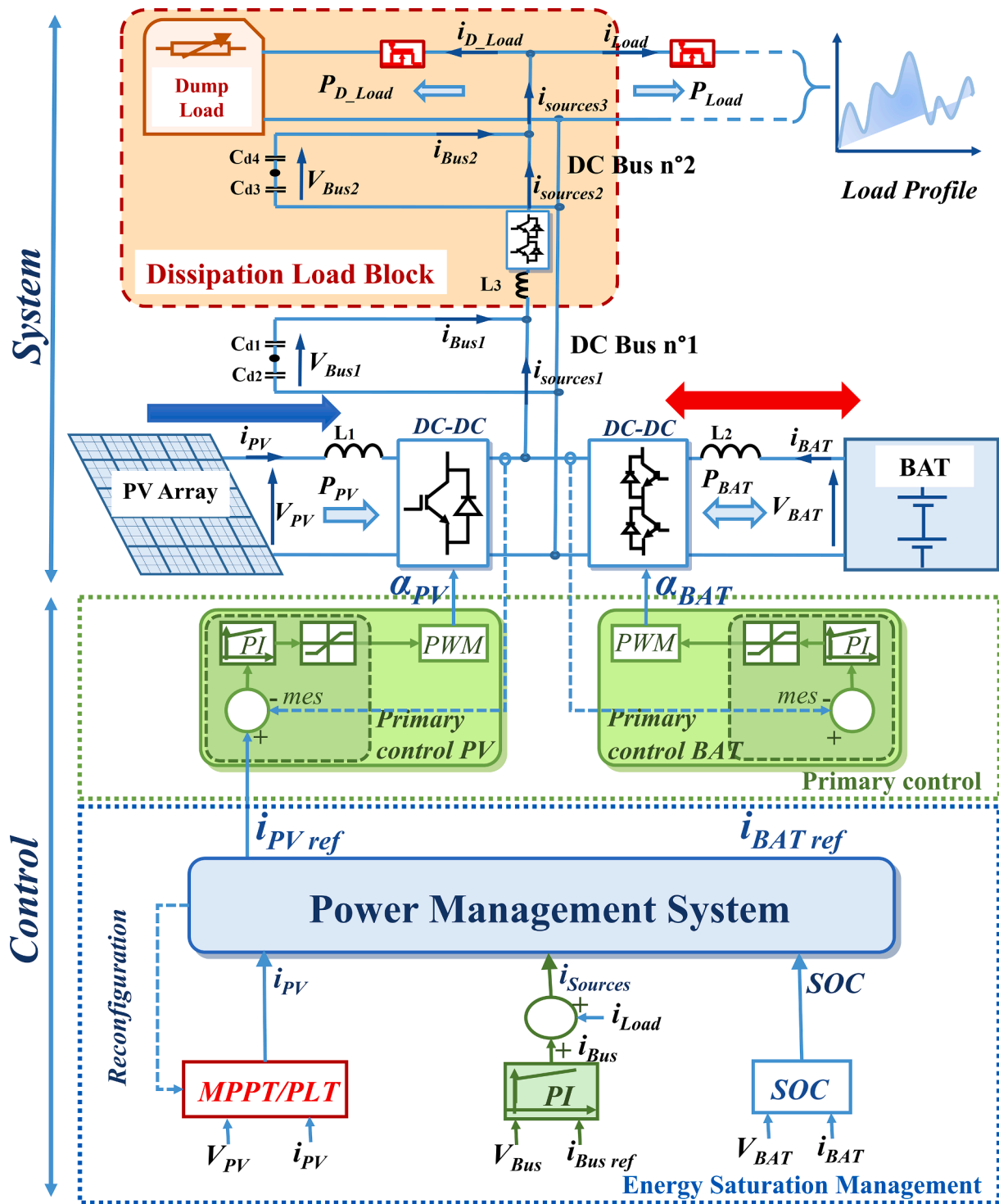


Fig. 4. Design and configuration of the proposed control and EMS supervision.

$$i_{BATref,max} = i_{BATmax} \times \min \left[1, \frac{(SOC - SOC_{Min})}{\Delta SOC} \right] \quad (4)$$

$$i_{PVref,max} = i_{PVmax} \times \min \left[1, \frac{(i_{load} - i_{pv})}{\Delta SOC} (SOC - SOC_{Min}) + i_{load} \right] \quad (6)$$

• i_{BATmin} is gradually set to zero when SOC approaches SOC_{Max} :

$$i_{BATref,min} = i_{BATmin} \times \min \left[1, \frac{(SOC_{Max} - SOC)}{\Delta SOC} \right] \quad (5)$$

• i_{PVmax} is gradually set to i_{Load} when SOC approaches SOC_{Max} :

3.2. Saturation management strategy

Depending on the state of PV and BAT sources, the system's limits must be considered by keeping the SOC at the rated value $SOC_{Min} > SOC < SOC_{Max}$ (nominal mode). Any change of power load causes a variation of the DC bus level. its measurement is therefore crucial to the controller

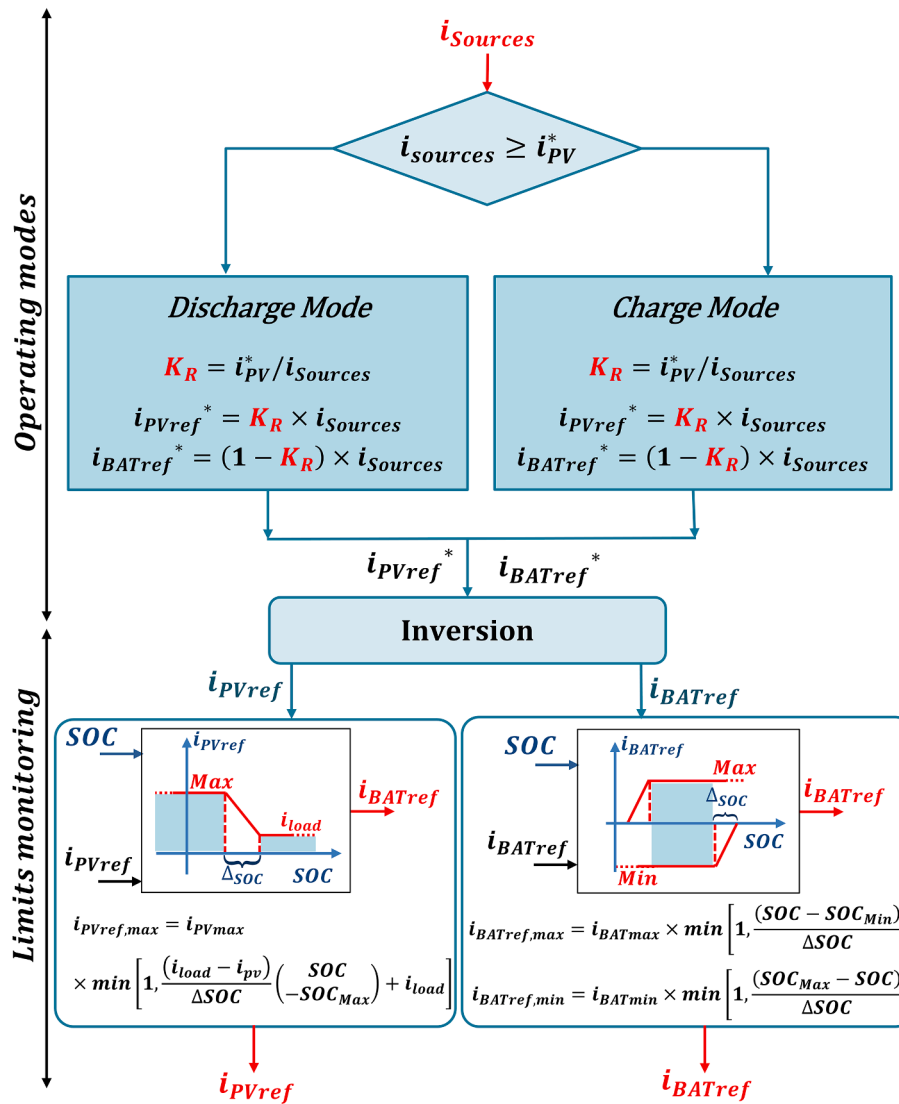


Fig. 5. Flow chart of control and power management of hybrid PV-Battery systems.

to determine power sources needed (Eqs. (7) and (8)).

$$\begin{cases} C_{Bus} \frac{dV_{BUS}}{dt} = i_{Cbus} = i_{Sources} - i_{Load} \\ i_{Sources} = i_{PV}^* + i_{BAT}^* = G_1 \cdot i_{PV} + G_2 \cdot i_{BAT} \end{cases} \quad (7)$$

$$G_1 = \frac{V_{BUS}}{V_{PV}} \text{ and } G_2 = \frac{V_{BUS}}{V_{BAT}} \quad (8)$$

Thus, the voltage control loop must regulate the DC bus voltage $V_{BUS}(t)$ and generates the sources current $(i_{Sources}(t))$ as illustrated in Fig. 4. After the needed power sources have been determined, the proposed controller should still be included (Eqs. (9) and (10)).

$$\begin{cases} C_{Bus} \frac{dV_{BUS}}{dt} = i_{Cbus} = i_{Sources} - i_{Load} \\ i_{Sources} = i_{PV}^* + i_{BAT}^* = G_1 \cdot i_{PV} + G_2 \cdot i_{BAT} \end{cases} \quad (9)$$

$$G_1 = \frac{V_{BUS}}{V_{PV}} \text{ and } G_2 = \frac{V_{BUS}}{V_{BAT}} \quad (10)$$

To realize this algorithms, a weighting factor k_R can be used to balance the distribution of power between sources and loads (Eq. (11)) depending to the working modes as described in Fig. 5.

$$\begin{cases} i_{PV}^* = k_{R1} \cdot i_{Sources} \\ i_{BAT}^* = (1 - k_{R1}) \cdot i_{Sources} \end{cases} \quad (11)$$

However; the reel use is distinct from the intended use, which forces the PV-BAT hybrid system to achieve its boundaries (saturated mode). The control scheme must take into account these possible cases of deflection. Indeed, for this purpose, a new cascade control loops is implemented (Fig. 4). This will permit to develop a control strategy using its weighting factor k_{R2} .

$$\begin{cases} i_{D_Load}^* = k_{R2} \cdot i_{Sources3} \\ i_{Load}^* = (1 - k_{R2}) \cdot i_{Sources3} \end{cases} \quad (10)$$

In the nominal mode, $k_{R2} = 0$. In saturated mode, two cases of the PV-BAT hybrid systems limits can be recognized:

- Strategy 'a' in Fig. 2: $k_{R2} = 0$. The BAT current is restricted at its maximum level, indicating that the required power demand is too excessive compared to the overall hybrid PV-BAT power generation. To avoid this saturation case, the load power is reduced so as to balance it to the maximum power given by the PV-BAT hybrid source. The regulation of V_{Bus2} achieves this objective (Fig. 4).

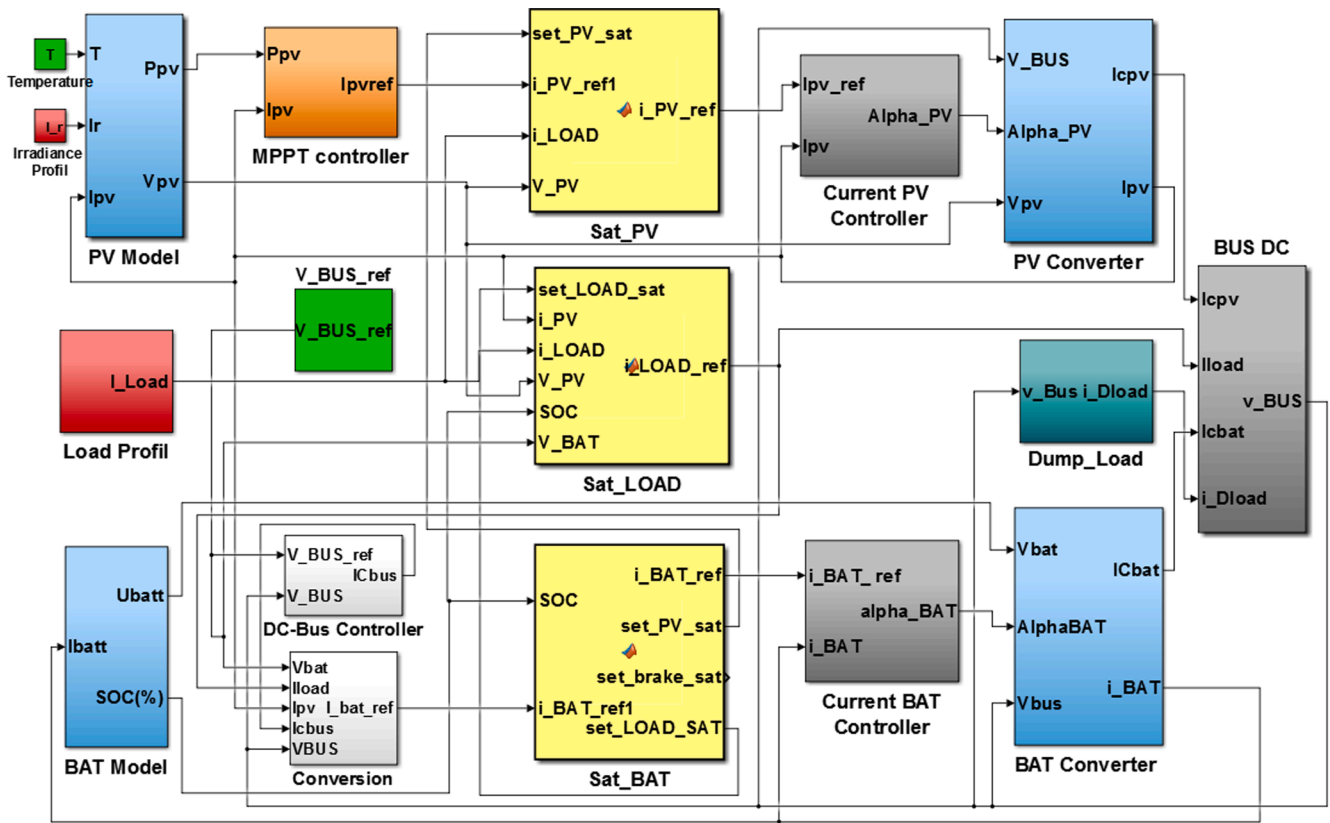


Fig. 6. Block diagram of the Matlab/Simulink used for the simulation.

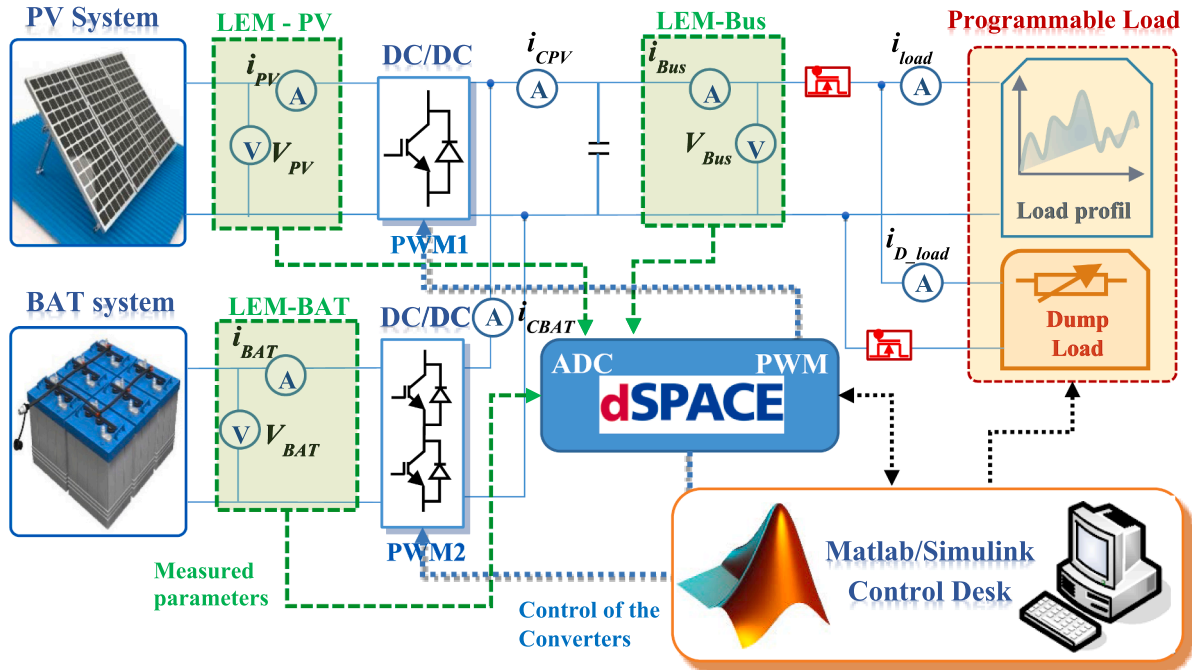


Fig. 7. Simplified scheme of the system test platform with integrated control.

- Strategy 'b' in Fig. 2: $k_{R2} = 1$. When the power given by PV (primary source) is too high compared to the power load, this leads to high charge current of the BATs which is limited to its minimum value. This indicate that BATs cannot store all the power. It is, therefore, necessary to switch on a dump load device, which means that excess of the power must be dissipated: V_{Bus2} control makes it possible to

reach this goal. Hence the utility of adding this additional component “dissipation load block” in the PV-BAT hybrid power system.

It can be deduced from this proposed approach that with a simple structure and architecture using conventional controllers we will be able to achieve our main objective of an efficient energy management system

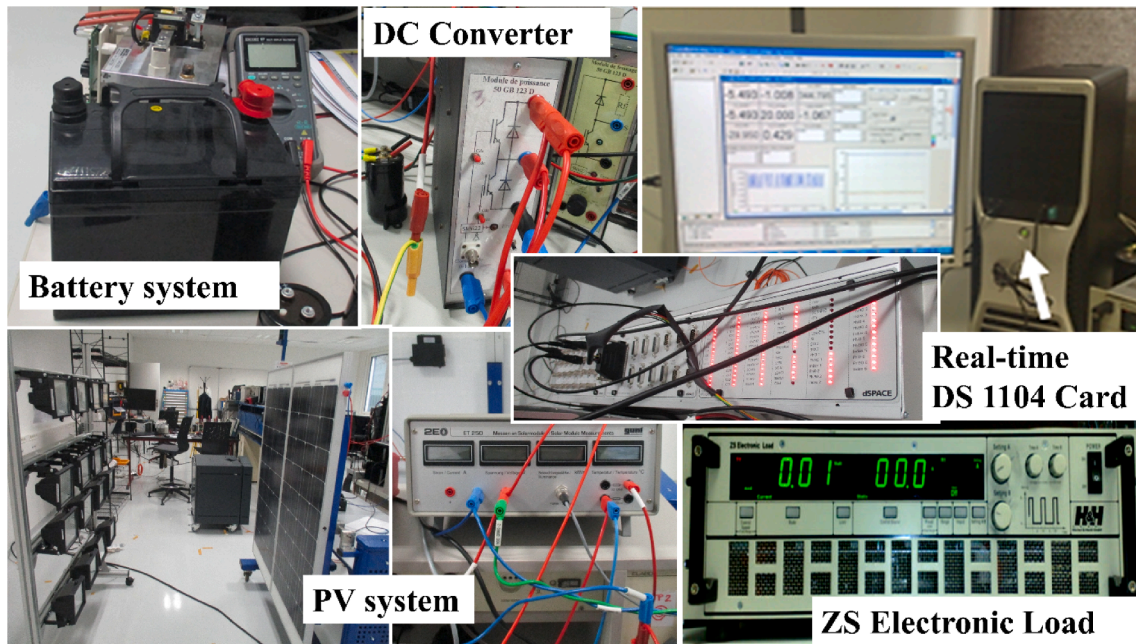


Fig. 8. The components of the experimental test.

Table 1
Electric characteristics of system.

PV: Parameter name	Value
Open circuit voltage	44 V
Short circuit current, I _{sc}	18 A
Voltage at maximum power point, V _{mp}	35.2 V
Current at maximum power point, I _{mp}	15 A
Series Resistance R _s	0.05 Ω
Efficiency at STC	15.9%
Irradiance at STC	1000 W/m ²
Temperature at STC	25 °C
BAT: Parameter Name	Value
Open circuit voltage	42 V
Rated Current	15 A
Internal resistance R _{int}	0.2 Ω
Inductors & Capacities: Parameter Name	Value
Inductors L _{PV} /L _{BAT}	100 μH
Rated Currents L _{PV} /L _{BAT}	25 A
Capacities C _{BUS}	4 mF
Optimal DC-Bus Voltage V _{BUSref}	50 V

to provide power and support situations of excess and deficit power availability. A hysteresis voltage range is used to avoid rapid transient switching between normal and saturated management.

4. Experimental setup description

In order to evaluate the proposed control strategy used for the system shown in Figs. 4 and 5, a comprehensive and extensive simulation/experimentation was carried out in different functioning modes and scenarios of the PV-BAT hybrid system partitioned in time intervals related on variations of SOC_{BAT} due of variations in demand and solar irradiance.

The designed control system is verified through the implementation of the comprehensive PV-BAT hybrid system model in MATLAB/Simulink. This model includes the proposed control strategy and energy saturation management system. The latter is applied for the PV system (Sat_PV), BAT system (Sat_BAT) and load (Sat_load) in accordance with a pre-determined control strategy. The designed Simulink model of the system is shown in Fig. 6.

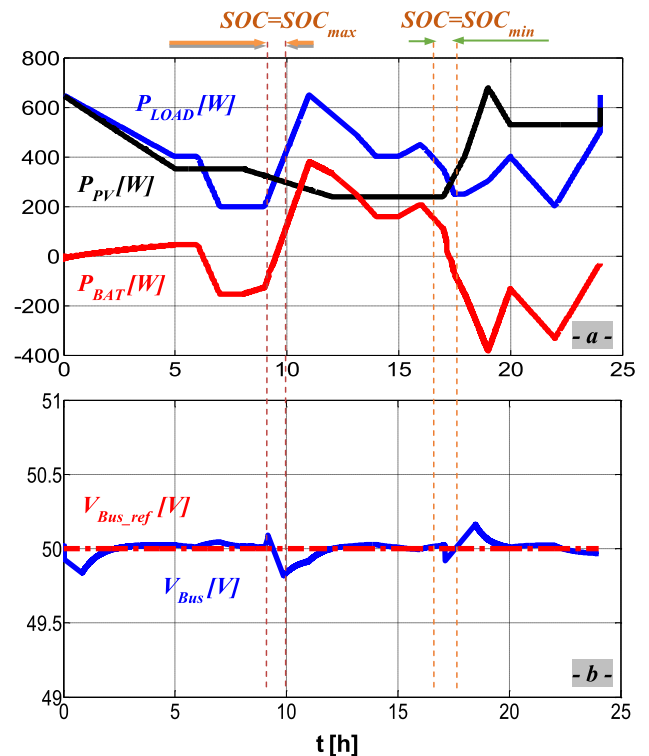


Fig. 9. System operation performances: Powers balance (a) Voltage of DC bus (b).

The structural schematic that illustrates the practical configuration is shown in Fig. 7, and the main components of the system test platform are given in Fig. 8.

A PV-BAT hybrid system comprising three sub-units was assembled in ESTACA'LAB: A PV panels, a lead-acid BAT and a power load unit consisting of a ZS (1806 [0–150 A]/ [0–60 V]) programmable electronic load. Uni-directional and bi-directional DC-DC converters are utilized for connecting PV and BAT systems, respectively, with DC bus. Current

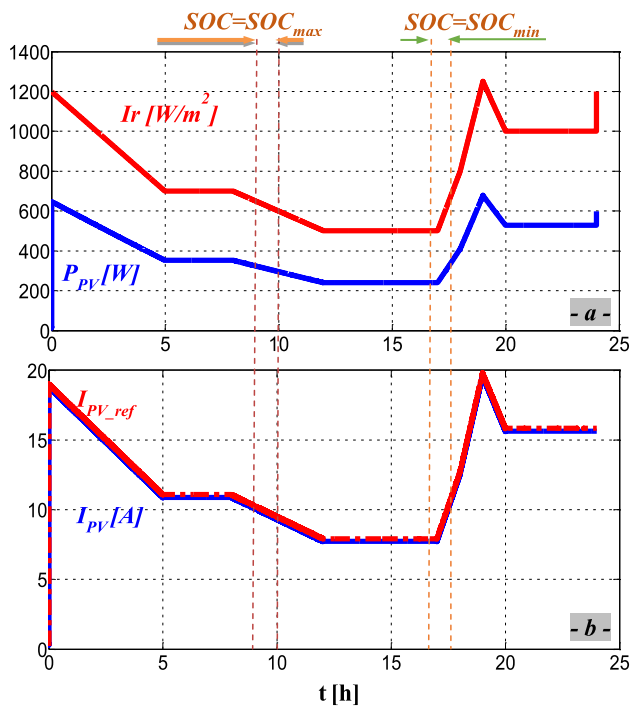


Fig. 10. Photovoltaic system operation performances: PV power and Irradiance (a) PV current output (b).

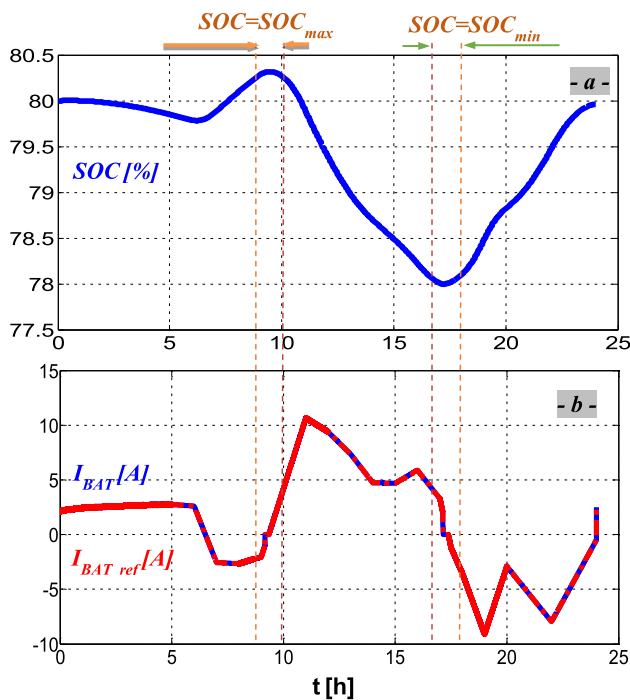


Fig. 11. Battery system operation performances: State of charge of BAT (a) BAT current output (b).

and voltage are measured through LEM LA55-P and LV20-P Hall effect transducers, respectively. The control algorithms implemented in Matlab/Simulink have been realized by DS1104 dSPACE board real-time testing. The parameters of the system and controllers are presented in Table 1.

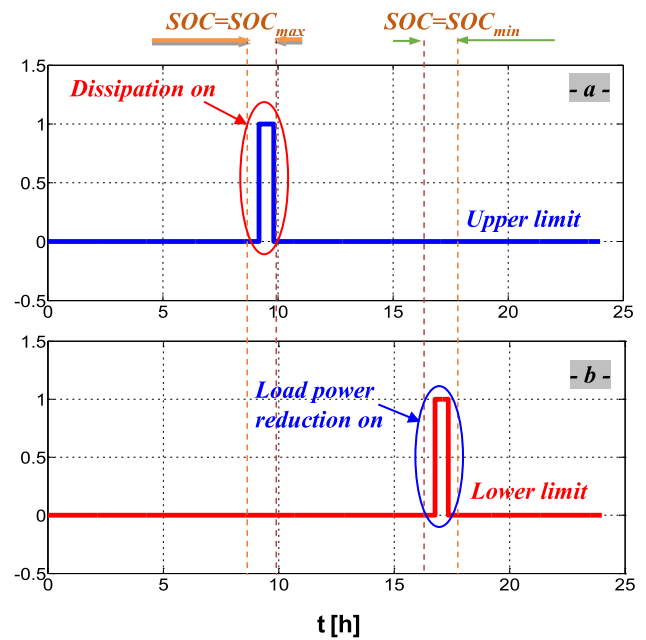


Fig. 12. Indication of the status of local sources limits protections.

5. Results and discussion

Figs. 9–12 show the simulation/experimentation results obtained using tow operational conditions normal and saturated mode.

Initially, the tests will be concentrated on test with normal conditions ($SOC_{min} > SOC < SOC_{max}$).

As can be seen in (Fig. 9a) the load demand is correctly balanced between the PV and BAT power sources. As the load demand and PV power vary, the BAT power automatically adapts its power in accordance with load level. It should support PV primary source to meet the load power demand, considering that in the proposed control, the BAT works as a buffering device to compensate the difference in power between PV and load according to the working mode. At 6 h:13 and 17 h:21 the BAT is commuted from the discharge mode to the charge mode when PV power generation increases, and the BAT is commuted from the charging mode to the discharging mode when solar irradiation decreases at 9 h:49.

In addition, the fluctuations of the DC bus voltage V_{BUS} is maintained within the acceptable margin in Fig. 9b. The voltage variation resulting from the power variations of the PV and the load is greatly minimized by applying the proposed control strategy. According to the comparison with other approaches given in Wang et al. (2013), Jin et al. (2014) and Oliveira et al. (2016), showing that the control algorithms proposed in this paper has the fastest power balance speed and the lowest DC bus voltage fluctuations; the reference $V_{BUS} = 50$ V is maintained perfectly, a very small overflow ($<1\%$), no steady-state faults are shown.

These results prove that the control strategy is working properly for power balancing and demonstrate the effectiveness of the designed control for DC bus voltage regulation.

Fig. 10b shows the output current of PV system. The PV power generation is tuned to the MPPT proportionally to the irradiance I_r in Fig. 10a. When the BAT SOC approaches SOC_{max} , the PV operating mode is switched from MPPT to PLT for maintaining the steady state of the DC bus voltage. Whereas, this transition of the PV operating state will be executed only when the voltage of DC bus attains the maximum limit of Oliveira et al. (2016), which will lead to great deviations of the voltage.

The BAT charging and discharging current is shown in Fig. 11b. The corresponding state of charge SOC of the BAT is shown in Fig. 11a. It should be noticed that during discharging mode, the sign of BAT current changes for absorbing the excess of power in the DC bus while in

recovery mode. When i_{BAT} is negative that signifies BAT absorb energy and when i_{BAT} is positive that indicates BAT supply load.

Moreover, for the closed-loops currents, the currents (i_{BAT} and i_{PV}) closely followed their references during normal and saturated modes (Figs. 10b and 11b), which demonstrates the pertinence of the inner control. It shows the power improvement ability of a supervised PV-BAT hybrid system and the complementarity of PV and BAT to satisfy steady-state and the transient power loads.

The second step of the tests consists in validating the effectiveness of the limits control and power management in saturated mode to prevent damage when the components of the hybrid PV-BAT system are forced by the load to work within their intrinsic limits. To this end, two cases can be considered in this experimental setup: a upper limit saturated functioning and a lower limit saturated operation at time ranges [9 h:10; 9 h:49] and [17 h:09; 17 h:21] respectively during which local sources limits control take place (Fig. 12a and b) and control algorithm changes as described in Section 3.

The first case starts when the BAT'SOC attains its upper limit (SOC_{max}). In this precise time, saturation of the local sources occurs, the PV current is reduced to load current (PLT) (Fig. 10b) and the minimum current limit of BAT ($i_{BAT,min}$) is reduced down to zero (Fig. 11b), in order to avoid any further charging of the BAT. These actions will instantaneously break the power balance and lead to a rapid increase of the voltage of the intermediary DC Bus N°1. During this process, the control strategy switches from the nominal algorithm to the saturated control architecture (Figs. 4 and 5). Furthermore, as the load is in recovering mode for the duration of this state, the voltage DC Bus N°2 voltage rises considerably: k_{R2} is tuned to one and *dump load* is utilized for regulating V_{Bus} by exploiting the dissipation load device. k_{R2} is returned to zero once V_{Bus} back to its reference (50 V). Then, the control algorithm returns to its nominal strategy and the two sources BAT and PV supply the loads.

Symmetrically, when the second state begins, i.e. once the BAT'SOC reaches its lower limit (SOC_{min}), saturation of the local sources occurs and the control system passes into saturated mode. Consequently, in this case, the load power is reduced to the PV power (Fig. 9a) and the maximum current limit of the BAT ($i_{BAT,max}$) is reduced to zero (Fig. 11b), to avoid any further BAT discharging. Once V_{Bus} back to its reference (50 V). Then, similarly to the first case, the control system returns to its nominal algorithm when V_{Bus} reaches its reference voltage.

The obtained results prove the power enhancement capability by applying the proposed hybrid system controller. These results prove the effectiveness of the proposed control strategies in different modes: normal mode and saturated mode. The strategy proposed has a functionality to cope with working conditions through the use degree of freedom allowed by coefficient K_R enabling the overall system dynamics to be adapted in accordance with the working modes. The results of Fig. 9b can illustrate the smaller fluctuation and deviation in DC bus voltage compared when the proposed saturated control strategy is employed.

6. Conclusion

This paper was mainly focused on the limits control and energy saturation management strategy for large-scale and applications of hybrid PV-BAT power systems. It was consisted with the optimization of power management of hybrid PV-BAT systems to ensure the energy distribution available from the PV array, BATs, and load demands. Suggested control strategy relies on enhancing the regulation of DC bus voltage by using PV as the primary source with an adaptive MPPT/PLT algorithm developed as part of our optimized proposed control and BAT as an additional source for system efficiency performance of hybrid PV-BAT systems. The BAT linked to the PV system's DC bus can improve the dynamic efficiency of the system by regulating BAT charging / discharging based on the power management oversight suggested when the system is subject to variable disturbances. The mechanisms for

managing system limitations and saturation is included in the control strategy to guarantee the safe and effective use of the system. Saturation management therefore implied dissipation system and regenerative break when the state of charge SOC'BAT of BATs reaches its upper or lower limits respectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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