Power Flow Control of a Hybrid Battery/Supercapacitor Standalone PV System under Irradiance and Load Variations

N. E. Zakzouk, R. A. Lotfi
Electrical and Control Engineering Department
Arab Academy for Science, Technology and Maritime Transport
Alexandria, Egypt
nahlaezzeldin@hotmail.com

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Abstract—**PV standalone systems are challenged by the PV intermittent nature, hence integrating energy storage systems (ESS) is mandatory. In this paper a hybrid battery/supercapacitor ESS is employed, in a standalone PV system, to maintain continuity in power supply. Supercapacitors (SC), featuring fast charge/discharge rates, will store the transient energy peaks reducing battery required capacity, increasing its life span, and minimizing its replacement costs. Moreover, a control scheme is presented to manage the power flow between generation and load sides, thus fulfilling load demands and maintaining DC-bus voltage stability. In this strategy, a protection modification is proposed to prevent battery overcharge, thus limiting its degradation and improving system reliability. All the latter results in a robust PV system with a longer-life battery and capable of preserving energy balance at the DC-bus even at sudden changes. The proposed system effectiveness is verified using MATLAB/Simulink under different scenarios of load and irradiance variations.**

Keywords—Battery, Hybrid ESS, Power flow control, PV off-grid, Supercapacitors

I. Introduction

Increasing energy concerns and depletion of conventional sources made it mandatory to explore and expand the use of the renewable alternatives [1]. PV solar energy is a promising clean noiseless and maintenance-free candidate [2]. Moreover, it is considered a cost effective solution in many off-grid applications, especially in locations far from the utility [3]. However, the intermittent nature of PV, due to its dependency on the surrounding weather conditions, made it challenging to preserve a reliable robust standalone service [5-6].

Standalone PV systems are flexible modular sources that are designed to operate independently of the utility grid. Hereby, they are considered since they are convenient for off-grid applications in remote areas, where grid supply is inaccessible or unreliable [4]. However, they should be equipped with an energy storage system (ESS) as a backup [7]. The latter balances the difference between generated power and the consumed one i.e. store the excess generated power during high irradiances, while maintain a stable power supply to the load when the sunshine is insufficient (at night or on cloudy days) [8]. Traditionally, PV systems use batteries as the main energy storage device however problems related to charging and discharging efficiency and comparatively short lifetimes arise. Although batteries possess high energy density that makes them convenient for steady low frequency power exchange, they show low power density. The latter means that batteries have low charge/discharge rates i.e. sudden power fluctuations (either due to load power surges or irregular PV power generation) interrupt their charge/discharge cycles and eventually degrades their lifetime [9].

Oppositely, supercapacitors (SC) possess more than ten times higher power density, thus extremely faster charging/ discharging rates and higher efficiencies comparatively [10]. This makes them the best choice for high frequency fast power exchanges. Another merit for SC over standard batteries is their life time and cycles number which are above 500 times more [11]. Moreover, they are light in weight, maintenance-free, less toxic and environmentally safe since no chemical reactions occur when SC are charged [12].

Hence, to preserve system stability and eliminate power transients' impact on battery's life, the battery/supercapacitor hybrid energy storage system (HESS) principle has been introduced [13, 14]. In this hybrid system, batteries are combined with supercapacitors. Batteries with their high capacity fulfill a steady energy supply while SC with their high power density and fast response supply the instant peak powers during transients. Thus, stress on battery is reduced, its life span is increased, high battery replacement costs are eliminated and system reliability is improved [15-17].

Battery/SC HESS are normally divided into passive, semi-active and active topologies based on the storage elements connection to the DC-bus [10]. In passive HESS, storage elements are directly connected to the DC-link. On the other hand, the semi-active topology is when only one element is coupled to the DC-bus via a bidirectional DC-DC converter. Finally, when both elements are connected to the bus through bidirectional choppers, it's considered the active topology. The latter improves the HESS flexibility and enhances the entire system performance [18]. Based on the applied ESS topology with the considered off-grid PV system, there should be an energy management strategy capable of achieving PV maximum power point tracking (MPPT), coordinating power sharing between battery and SC and preserving power balance between the generation and consumption sides [19-24].

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In this paper, a standalone PV system is considered featuring an active battery/SC HESS. A strategy is introduced to control power sharing between the PV and ESS elements, to guarantee energy balance and preserve voltage stability at the DC-bus. The applied ESS control forces the SC to deal with fast transients while the battery compensates for steady power drifts. Moreover, PV control is modified to adjust battery charging in accordance with its maximum state of charge (SOC), thus avoiding its degradation and increasing its life time. Simulation tests using MATLAB/Simulink are carried to verify system effectiveness under varying load and irradiance profiles. To reassure the latter, system performance is retested with a commercial load under real-time weather data. Results validated the proposed technique ability to fulfill varying load demands, maintain balance and eliminate battery overcharge.

II. System under Consideration

The considered off-grid PV system with the adopted active battery/SC HESS is shown in Fig. 1. The PV array and the ESS elements are coupled to a common DC-bus of 50V, via DC/DC converters, to supply a variable DC load of 1kW peak demand. The system is sized to steadily fulfill the load in accordance to the applied control scheme. System components ratings are given in Table I.

A 965W PV array is applied featuring 4 parallel strings with two series Waaree energies PV modules per string. P-V curves of each module for different irradiance conditions are shown in Fig. 2. The array MPP voltage at 1000W/m^2 reaches 34V, thus a boost converter is used to interface the array to the 50V bus. Regarding the ESS elements, a 32V, 29F super capacitor and a 24V, 14Ah lithium ion battery are applied. The latter is chosen among different battery types, due to its great sustainability to climate changes and long estimated lifetime [5]. Each of the ESS elements is coupled to the 50V DC-bus via a bidirectional converter to serve charging and discharging modes. Hereby, in **charging mode,** the bidirectional converter acts as a buck converter, conveying the energy from the higher voltage side (DC-bus) to the lower voltage side (ESS device). Whereas, it acts as a boost converter in **discharging mode** i.e. energy conveyed from ESS to DC-bus.

Buck mode; $$V_o = V_i D \tag{1}$$

Boost mode; $$V_o = V_i/(1-D) \tag{2}$$

where V_o, V_i, D are the DC/DC converter output voltage, input voltage and duty ratio respectively.

TABLE I. System Components' Ratings

System Components	Ratings
Waaree 120W PV panel At standard conditions	• Voltage at MPP (V_{MPP}) is 17V • Current at MPP (I_{MPP}) is 7.1A • Power at MPP (P_{MPP}) is 120.7W
PV array (2×4) At standard conditions	• V_{MPP} =2×17=34V • I_{MPP} = 4×7.1= 28.4 A • P_{MPP} = 965.6W
Load	50V, 1kW variable DC load
Battery	24V, 14Ah Lithium-ion
Supercapacitor	32V, 29F
DC-link voltage	50V
Inductors	$L_{PV} = L_B = L_{SC}$ = 0.5 mH
Switching frequency	15 kHz

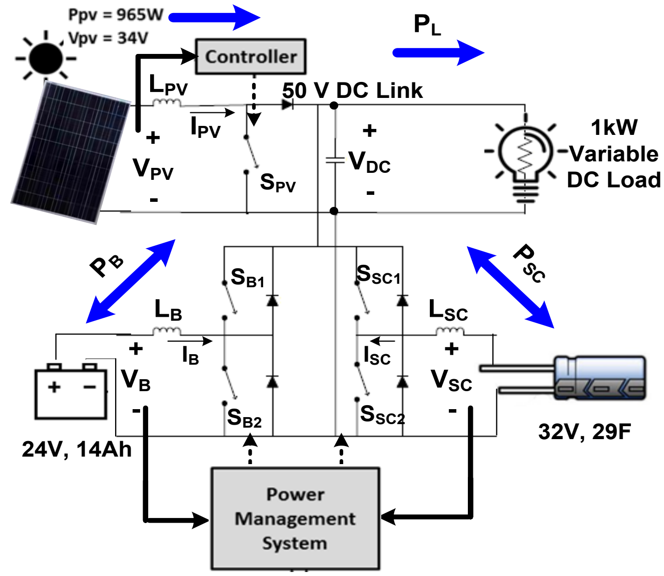

Fig. 1. Considered system schematic diagram

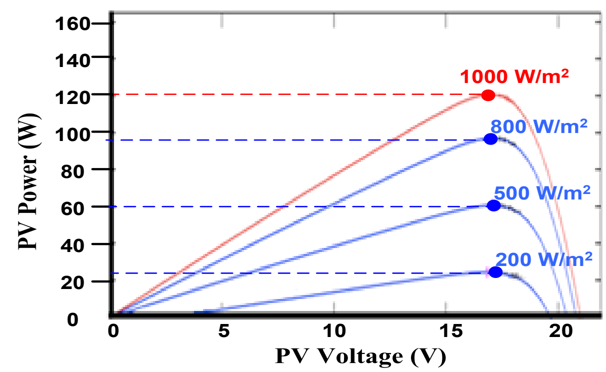

Fig. 2. P-V curves of Waaree energies WU-120 for different irradiances.

III. Power Flow Control

A power flow control strategy is introduced in this paper to preserve the required energy balance between the generation and consumption sides, thus marinating a stable DC-bus voltage at 50V. This includes the control of ESS elements' bidirectional converters thus coordinating power sharing between battery and SC. Moreover, it encounters PV boost converter control to achieve PV MPPT. A modification is proposed to shift from MPPT to DC voltage control mode when the battery is full to prevent battery overcharge.

A. ESS Control

As previously discussed, the SC is mainly added to absorb the transient peak energy that results from instant load changes or weather fluctuations, thus, minimizing battery charging stresses. To achieve this, power drift between generation and consumption sides will be divided into two components, the steady low frequency component (LFC) and the transient high frequency component (HFC). The battery will be responsible of the former while the SC will deal with the latter [21].

This control scheme includes three control loops as shown in Fig. 3(a). First, the DC-link voltage control loop to maintain the DC-bus voltage at 50V. The output of this loop generates the total reference current (I_{ref}) which should be compensated to eliminate any voltage drift i.e. any power drift, thus maintaining the required balance. Concurrently, I_{ref} is divided into two components; LFC and HFC. Thus, first it will pass through a low pass filter to extract its LFC ($I_{ref\text{-}LF}$) which will be the reference to the second loop which is the battery loop. The latter allows the battery to compensate for the LF average level of power drift. On the other hand, the reference current HFC ($I_{ref\text{-}HF}$) is compensated by the third loop which is the SC control loop. The reference of this loop ($I_{SC\text{-}ref.}$) is computed by $I_{ref\text{-}HF}$ and battery error current ($I_{B\text{-}error}$) as follows [21];

$$I_{ref-HF} = I_{ref} - I_{ref-LF} \tag{3}$$

The power ($P_{B\text{-}uncomp.}$) that is not compensated by the battery and has to be fulfilled by the SC is given by;

$$P_{B-uncomp} = V_B(I_{ref-HF} + I_{B-error}) \tag{4}$$

Thus, the reference current for the SC loop ($I_{SC\text{-}ref.}$) is;

$$I_{SC-ref} = \frac{P_{B-uncomp}}{V_{SC}} \tag{5}$$

where V_B, V_{SC} are the battery and SC voltages respectively.

Each of the discussed loops encounter a PI controller. The battery loop output then undergoes PWM to produce switches gating signals of the battery bidirectional converter ($S_{B\text{-}1}$ is activated for charging mode while $S_{B\text{-}2}$ is activated for discharging mode). Similarly, after PWM of the SC loop output, gating signals for SC bidirectional converter switches are produced ($S_{SC\text{-}1}$ for charging and $S_{SC\text{-}2}$ for discharging).

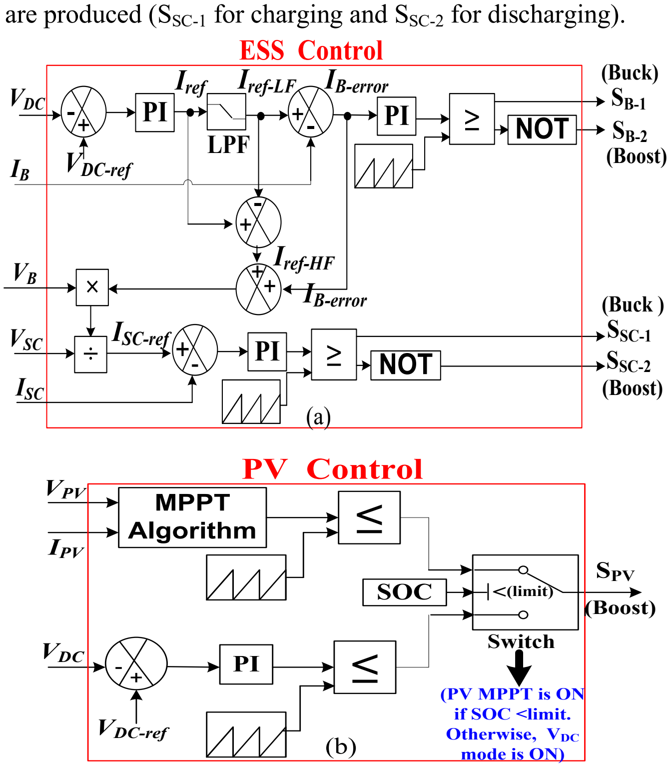

Fig. 3. Applied control scheme, (a) ESS control, (b) PV control

B. PV Control

The PV array boost converter is controlled using a MPPT controller to extract the exact PV maximum power under various weather conditions. In this paper a Perturb and Observe MPPT algorithm is applied [25]. However, in case PV power (P_{PV}) > load power (P_L), the excess steady power will be transferred to the battery even if it's full charge. This would cause battery degradation. Hence, an enhancement is proposed to solve this problem as shown in Fig. 3(b). In case of a fully charged battery (SOC reaches the maximum level), the MPPT is deactivated and DC-bus voltage (V_{DC}) regulation loop is activated. Hereby, PV just delivers the adequate power that stabilizes V_{DC} to 50V without interfering with battery.

IV. Simulation Results

To verify the proposed system performance and the applied control validity, the considered system is tested using MATLAB/Simulink for the following case studies: i) Scenarios for variation in irradiance and load demand and ii) Commercial load in July and December months in Egypt.

TABLE II. Test 1 Scenarios

Studied Cases	Parameters	Decision
Case 1 (t=0 : 1 sec) o $P_{PV} > (P_L + P_{Losses})$ o Battery SOC< limit Battery in charging mode	o Insolation =1000 W/m^2 o P_{Load} = 500 W o Battery SOC<98%	PV (MPPT mode) P_{PV} =965W → Load (500W) → Battery (425W-charge mode) → Losses (40W)
Case 2 (t=1 : 2 sec) o $P_{PV} > (P_L + P_{Losses})$ o Battery SOC< limit Battery in charging mode	o Insolation =800 W/m^2 o P_{Load} = 500 W o Battery SOC<98%	PV (MPPT mode) P_{PV} =760W → Load (500W) → Battery (215W-charge mode) → Losses (45W)
Case 3 (t=2 : 3 sec) o $P_{PV} > (P_L + P_{Losses})$ o Battery SOC=limit SOC is at mx limit so MPPT must stop & V_{DC} regulation is activated	o Insolation =800 W/m^2 o P_{Load} = 500 W o Battery SOC=98%	PV (V_{DC} mode) P_{PV} =575W → Load (500W) → Battery (reduced to 30W) → Losses (45W)
Case 4 (t=3 : 4 sec) o $P_{PV} < (P_L + P_{Losses})$ o SOC lessens due to battery discharge to compensate for drift	o Insolation =800 W/m^2 o P_{Load} = 1000 W o Battery SOC<98%	PV (MPPT mode) P_{PV} =760W and P_B =275W-disch. → Load (1000W) → Losses (35W)
Case 5 (t=4 : 5 sec) o $P_{PV} < (P_L + P_{Losses})$ o Battery SOC< limit Battery in discharging mode	o Insolation =500 W/m^2 o P_{Load} = 500 W o Battery SOC<98%	PV (MPPT mode) P_{PV} =480W and P_B =60W-disch. → Load (500W) → Losses (40W)
Case 6 (t=5 : 6 sec) o $P_{PV} < (P_L + P_{Losses})$ o Battery SOC< limit Battery in discharging mode	o Insolation =200 W/m^2 o P_{Load} = 500 W o Battery SOC<98%	PV (MPPT mode) P_{PV} =190W and P_B =355W-disch. → Load (500W) → Losses (45W)
Case 7 (t=6 : 7 sec) o $P_{PV} < (P_L + P_{Losses})$ o Battery SOC< limit Battery in discharging mode	o Insolation =0 o P_{Load} = 500 W o Battery SOC<98%	No PV output P_{PV} =0 and P_B =525W-disch. → Load (500W) → Losses (25W)

The main objective is to maintain the DC-link voltage at 50V and fulfill the load demand (and system losses as well) despite any variation of the load or the solar irradiance. This should occur without degrading the battery during transients or due to overcharge.

A. Different Scenarios of Varying Irradiance and Load

In this test, the considered system is tested under seven scenarios of load and irradiance variations. Table II presents the studied scenarios, corresponding power values and the corresponding energy management decision to achieve the required objective.

Fig. 4 shows that the DC link voltage is successfully regulated at 50V. In Fig. 5(a), it's denoted that the maximum PV power was accurately tracked according to the irradiance around the PV array. Fig. 5(b) shows the load demand and how it experienced sudden step up from 500 to 1000W at t=3sec then back to 500W at t=4sec. Analyzing the resulting steady power values of PV, Load and battery, presented in Table II and Fig. 5 for each case, it's proved that the required energy balance is guaranteed and the load is always fulfilled.

Zooming into Fig. 5(c), it's clear that the SC shows fast response in compensating the peak transient powers during either load or irradiance changes. Thus, this relief the battery from these peaks stress to take the lead to compensate for any steady drift between supply and load powers.

In the first two cases, that battery succeeded to store the excess power since the PV extracted power was greater than the total load power and system losses. In case 3, although there was no variation in the irradiance nor the load demand, the battery became almost fully-charged (SOC=98%). Hence, the PV control was shifted from the MPPT mode to the voltage control mode and PV power decreased to just fulfill load demand to protect battery from overcharge. In case 4, the battery started to deliver power since the load increased to the double which was over the PV capacity in this case. Finally, in the last three cases, the load demand returned back to its initial value (500 W). However, the irradiance kept decreasing till its absence in the last case. Thus, the battery continued to share with PV in load supply till taking the lead in the last case.

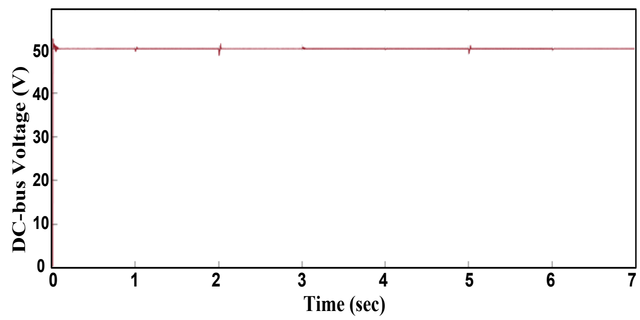

Fig. 4. DC-bus voltage during simulation test1

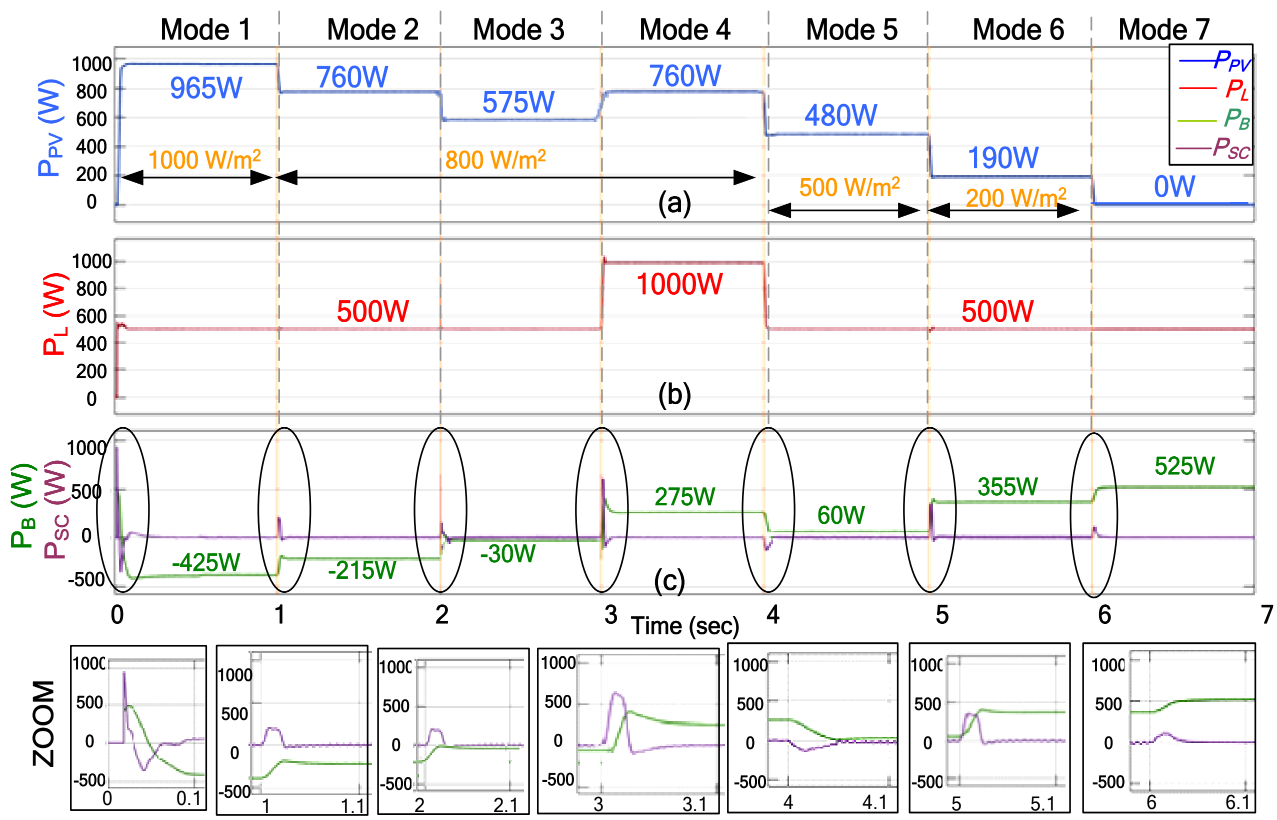

Fig. 5. Test 1 simulation results, (a) PV extracted power (P_{PV}), (b) Load power (P_L), (c) Battery and SC powers (P_B & P_{SC})

B. Varying Commerial Load under Real Irradiance Data

After system validation, results are reassured by another test with real-time data in summer and in winter. The considered system is tested with a commercial load in an office. This office working hours are from 8a.m till 5p.m. and then another hour with minimal load for cleaning up. Load data are given in Table III for July and December months [26]. It's noted that in December the demand was reduced in working hours by 200W since two fans of 100W each are off.

TABLE III. TEST 2 LOAD AND IRRADIANCE DATA [26, 27]

Case	JULY		DECEMBER	
	P_L (W)	Irradiance (W/m^2)	P_L (W)	Insolation (W/m^2)
(8a.m→12p.m)	566	300→1000	366	53→623
(12p.m→1p.m)	950	1000→1100	750	623→622
(1p.m→2p.m)	743	1100→900	543	622→570
(2p.m→3p.m)	760	900→800	560	570→427.5
(3p.m→4p.m)	532	800→700	332	427.5→285
(4p.m→5p.m)	532	700→500	332	285→91
(5p.m→6p.m)	56	500→400	56	91→0

Moreover, irradiance profiles in both months are driven at a location to be the supposed office location and shown in Fig. 6 [27]. Based on the considered load and irradiance curves, the system was tested for each month. Fig. 7 parts (a) and (b) show the system attained powers of PV, load, battery and SC in July and December respectively.

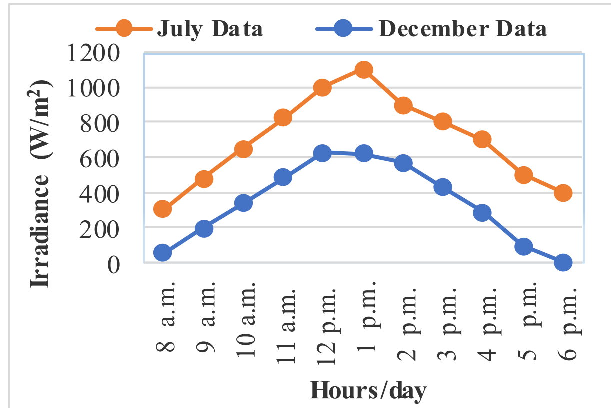

Fig. 6. Irradiance real data in July and December

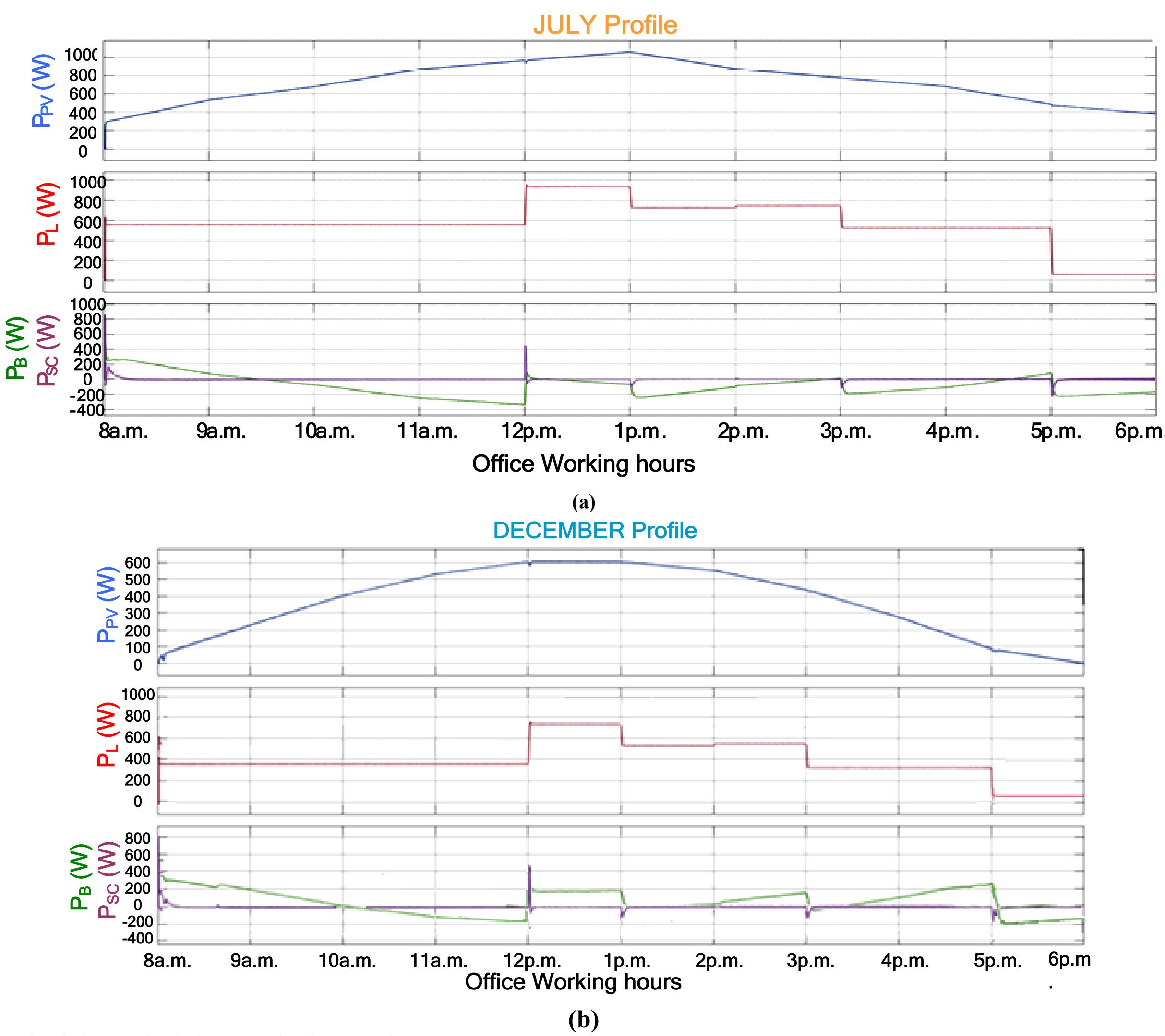

Fig. 7. Test 2 simulation results during, (a) July, (b) December

In both figures, the PV power is efficiently tracked according to the irradiance profile of each month. Regarding the load power, it's clear that it decreases in December by 200W as explained earlier. Finally, the SC deals with abrupt load power transients while the battery is responsible for steady power exchange. Since December show less levels of irradiance, battery will show more contribution in supplying power even though the load demand decreased in this month.

The results show that for all cases, the overall control strategy efficiently managed the power flows among system elements. Thus, it fulfilled the varying load demand, achieved the required balance and preserved DC voltage stability. Moreover, the SC role was clear in improving system performance and providing the required buffer at transients. Finally, the proposed enhancement, protected the battery against overcharge to add to system reliability.

V. CONCLUSION

In this paper, a standalone PV system, featuring a hybrid battery/supercapacitor ESS, is proposed and simulated under load fluctuations and non-uniform irradiance conditions. Results validated the proposed technique capability in maintaining voltage stability and preserving power balance at the DC-bus in addition to eliminating battery overcharge. Moreover, the role of SCs was reflected in supplying transient peaks, resulting in batteries with longer life span and reduced size and cost. Finally, these results were reassured when testing the considered system with a commercial load under real-time solar irradiance data during a summer month (July) and winter month (December). Experimental prototype implementation of the proposed system is to be considered.

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