JJEE
Volume 2, Number 1, 2016
Pages 1-12
Jordan Journal of Electrical Engineering
ISSN (Print): 2409-9600, ISSN (Online): 2409-9619

Energy Management and Control of a Stand-Alone Photovoltaic/Ultra Capacitor/Battery Microgrid

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Received: December 2, 2015 *Accepted: December 26, 2015*

Abstract— In this paper, the aggregation and implementation of a new energy management method in a microgrid power system is presented. Energy management is based on the use of a hybrid storage system. The Ultra Capacitors are used for facing high frequency variation of the load, such as in transient state, while batteries are in charge of slow load /source variations. Early ageing of the batteries is therefore avoided. The advanced control system proposed in this study allows choosing a suitable storage element in order to face the production/consummation variation correctly. The whole system, including a PV generator, hybrid storage system and realistic load, all connected to a common DC-bus, is first modeled. The simulations using Matlab are then carried out to confirm the good performances of the proposed energy management and associated control system.

Keywords— Energy management, hybrid power system, microgrid, photovoltaic.

I. INTRODUCTION

The last generation of power systems consists of large power plants that are usually located far from consumption points. The generated power must be transferred through long and expensive transmission lines. In this case, control centers are required to continuously ensure the quality of the power, voltage and frequency [1]. Nevertheless, in the near future, this procedure will be changed because of the increasing number of interconnected microgrids [2]. A microgrid is a small grid with multiple Distributed Generators (DGs), Energy Storage System (ESS) and loads. In practice, microgrids can operate either in a grid-connected or islanded mode, with a possibility of seamless transitions between them [3].

Nowadays, islanded microgrids have been used in applications like avionic, automotive, marine, residential and rural areas [4], [5]. In these applications, generally different sources and loads are connected to a common bus. In such embedded or safety critical applications, a high level of system reliability is mandatory [6]. One of the most important issues affecting the reliability of the system is the energy balance of the common bus. To ensure energy balance between sources and loads in a system, an effective energy management strategy is required.

Several papers have studied energy management methods in microgrids [4], [5], [7]-[10]. In these works, different types of energy sources, such as wind energy, fuel cell, photovoltaic and micro turbine are considered. But, due to the decrease in its installation cost in recent years, photovoltaic (PV) generation has emerged as one of the major DG sources and is widely used in microgrids [1], [11]-[13]. However, the intermittent behavior of the sun irradiation makes the PV generation an uncertain power source. The major challenge to use the photovoltaic system as a main power supply is that PV power is not available during night and cloudy days. That is why the integration of the ESS is needed to reduce the uncertainty of the renewable generation and to enhance the stability and reliability of such microgrids [7].

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On the other hand, DC microgrids are more efficient and interesting because DC generators and storages do not need AC-DC converters for being connected to dc microgrids.
In this paper, an energy management strategy is studied and verified by means of simulation on a DC microgrid. The studied power system consists of a PV source, a battery pack, an ultra capacitor and some different loads, which are also connected to a common DC bus.
In the following section, the studied microgrid is first introduced. In section III, the system modeling is explained and detailed. The energy management strategy and system control are presented in section IV. Simulation results, which validate the performances of the proposed method, are presented in section V. The paper is finalized by some conclusions in section VI.

II. System Description

The studied DC microgrid is shown in Fig. 1. This system consists of a photovoltaic (PV source) and hybrid storage system and some loads, which are connected to a common DC bus. A mono-directional boost converter is used in order to connect the PV source to the DC bus. This converter has two roles in the system: first, it steps the voltage of the PV up to the DC bus voltage; and secondly it allows achieving the maximum produced power by applying a MPPT (Maximum Power Point Tracking) algorithm. The Ultra Capacitor (UC) has fast dynamics, so it can be added to smooth fast fluctuations of the PV power and the loads in short-term (from seconds to minutes). The UCs are connected to the DC bus through a bi-directional DC-DC converter to ensure the DC bus voltage stability. The dynamic of the battery pack is slower than that of the UC. Therefore, batteries are used to smooth the difference between the PV produced power and load demand in long-term (from minutes to hours).

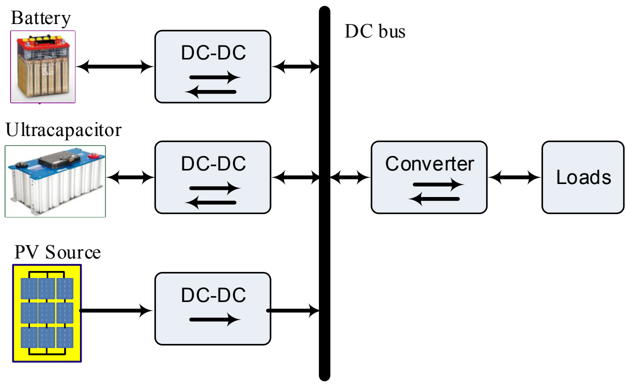

Fig. 1. Studied microgrid

As it is mentioned earlier, the stability of the system can be affected by losing the instantaneous balance between supply and load. Therefore, an energy management algorithm is needed. System modeling and system control are detailed in the following sections.

III. System Modeling

A. Photovoltaic Module

A real PV generator consists of the whole assembly of solar cells, connections, protective parts and supports. This paper only focuses on the cell/module/array modeling. Solar cells are based on a p-n junction fabricated in a thin wafer or layer of semiconductor (usually silicon); and its *I-V* output characteristic is exponentially similar to that of a diode. Therefore, the simplest equivalent circuit of a solar cell which many papers address is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell (photocurrent (I_{ph})). The increasing sophistication, accuracy and complexity can be introduced to the model by adding such parameters as the temperature dependence of the diode saturation current and the photo current (I_{ph}), series resistance R_s, shunt resistance R_{sh} and diode quality factor n [14]-[16]. In this paper, a model of moderate complexity was used as shown in Fig. 2a. The net current I is the difference between the photo current I_{ph} and the normal diode current ID:

$$I = I_{ph} - I_D = I_{ph} - I_0(e^{\frac{q(V+IRs)}{mkTc}} - 1) \quad (1)$$

where m is the idealizing factor, k is the Boltzmann's gas constant, T_c the absolute temperature of the cell, q the electron charge and I_0 the dark saturation current, which strongly depends on temperature. A PV module is made of some PV cells, which are encapsulated with various materials to protect cells and electrical connectors from the environment. Normally, manufacturers propose PV cells in modules consisting of N_{MP} parallel branches, each with N_{MS} solar cells in series. A series-parallel composition of some PV modules makes a PV array.

B. Ultra Capacitor

Among the models presented in the scientific literature, the model proposed by Zhang and Yu in [17] is used in this paper. Fig. 2b shows this model. In this model, the current i_{UC} is used as an input; and it limits the UC operation in safe area (between the high and low voltage limits). This model consists of three parameters: a capacitance C_{UC}, an equivalent series resistance R_{UCS} representing the charging and discharging resistance, and an equivalent parallel resistance R_{UCP} representing self-discharging losses. The voltage v_{UCi} over the capacitance C_{UC} is the open-circuit voltage.

C. Battery Pack

Various battery models are published in the literature. A commonly used one was proposed in [7], [17] and [18] as shown in Fig. 2c. The relationship among the battery terminal voltage v_{bat}, open-circuit voltage V_{emf}, charge/discharge current i_{bat}, internal resistance R_1 and a parallel R_C circuit which illustrates charge transfer and the diffusion between the electrode and the electrolyte [7], [18] is expressed by (2):

$$V_{bat} = V_{emf} - I_{bat} * (R_1 + \frac{R_2}{1+C_b*R_2*s}) \quad (2)$$

In (3), the battery SOC (State Of Charge) as a function of SOC_0, A_{bat} and i_{bat}, the initial value of battery SOC, the battery capacity and current is provided.

$$SOC = SOC_0 + \frac{1}{3600A_{bat}} \int i_{bat} dt \quad (3)$$

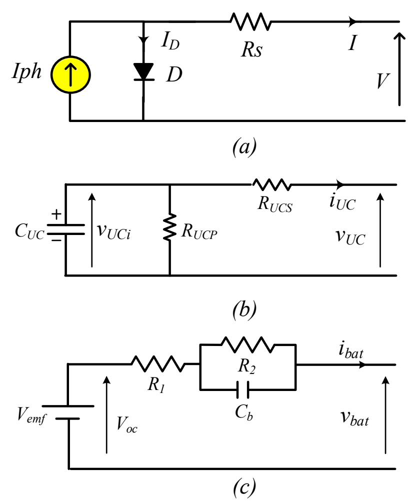

Fig. 2. a) Equivalent circuit of a solar cell, b) ultra capacitor model, c) battery model

IV. Energy Management Strategy and Control

To stabilize the DC bus voltage and control the studied microgrid (presented in Fig. 1), a global control loop for system energy management is proposed. This control is based on DC bus energy balancing. Since the PV source of the system has a slow dynamic and uncertainty in energy production, a fast load variation may lead to a high under/over voltage in the DC bus and affect the controllability of the system. Therefore, applying a suitable control on the UC efficiently controls DC bus voltage during fast load variations.

To control and optimize energy management in DC networks, some methods have been presented in the literature [3], [7], [13], [19] and [20]. In this paper, classic Proportional-Integral (PI) controllers are used to control the system. To optimally manage the energy flows between various components in a DC microgrid, the following basic requirements should be considered:

- The instantaneous algebraic sum of all powers in and out of the DC bus must be zero.
- The PV source is connected to DC bus via a boost converter controlled by a MPPT algorithm.

The strategy of energy management and related control system proposed in this paper will be explained in the following sections.

A. DC Bus Voltage Control

A synoptic of the studied microgrid and the DC bus voltage control is shown in Fig. 3. The energy of the DC bus (y_{dc}) varies according to the power consumed or supplied by the connected subsystems. If we maintain constant y_{dc}, the DC bus voltage can be regulated to its set value (V_{dcref}). Recall that the power of the PV source depends on irradiation and temperature which are controlled by MPPT. The control strategy used for the battery pack and the UC has different dynamics and objectives:

- The UC, which is the fastest energy storage element, is responsible for regulating the DC bus when a rapid change appears in the load.
- The battery pack is supposed to regulate the energy stored in the UC.

As Fig. 3 shows, DC voltage control consists of two loops. The outer loop's role is to regulate the energy y_{dc}, while the inner loop regulates the current i_{uc} of the UC (see Fig. 3). The stored energy in the DC bus capacitor is defined by the following equation:

$$y_{dc} = \frac{1}{2} C_{dc} v_{dc}^2 \tag{4}$$

As we have already mentioned, the sum of all powers in and out of the DC bus must be zero at any time. The derivative of the y_{dc} may be expressed by (5). The p_{pv}, p_{bat}, p_{uc} and p_L are powers provided (or absorbed) by the PV, the battery, the UC and the load respectively.

$$\dot{y}_{dc} = p_{dc} + p_{bat} + p_{pv} - p_L \tag{5}$$

The reference value of the UC's power (p_{ucref}), which compensates rapid load variations, can be expressed as in (6), where the $p_{uc/dc}$ is the power that must be provided (or stored at a given time) by the UC. This assures the DC bus energy (y_{dc}) regulation.

$$p_{ucref} = p_{uc/dc} - p_{bat} - p_{pv} + p_L \tag{6}$$

To calculate the reference of the UC's current (i_{ucref}), $p_{uc/dc}$ is divided by the voltage measured at the UC.

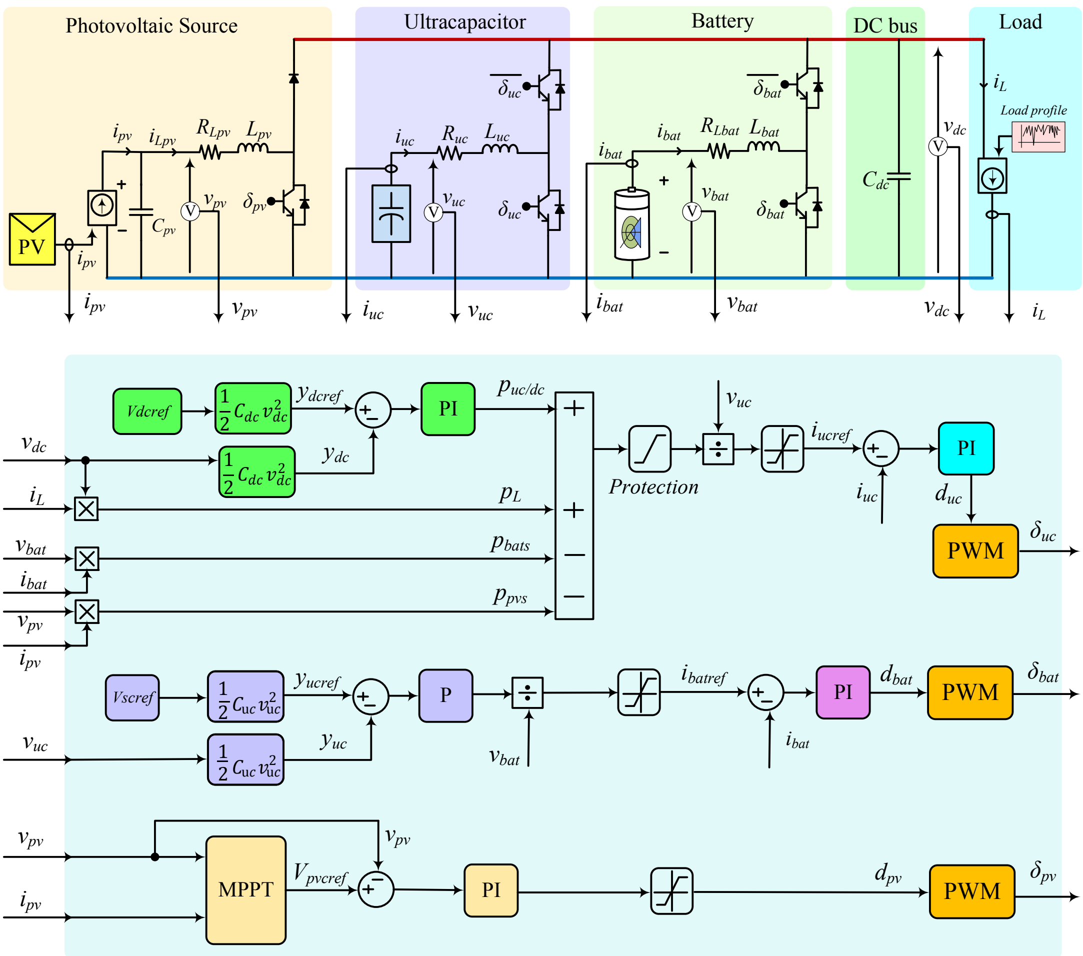

Fig. 3. Detailed HDCPS with the converters control

B. *Ultra Capacitor Energy Control*

According to the control strategy previously established, the battery pack regulates the energy of the UC as follows:

$$y_{uc} = \frac{1}{2} C_{uc} v_{uc}^2 \tag{7}$$

For this, a control architecture including two loops is proposed. The outer loop is responsible for the regulation of energy y_{uc} stored in the UC, whereas the inner loop is used to regulate the current of the battery at its set-point value. The control method is similar to that used for the control of the y_{dc}. Fig. 3 shows the control strategy.

C. PV Maximum Power Extraction and Control

In order to optimize the operation of a PV source, it is important to follow the maximum power by a MPPT algorithm. The search for the optimal operating point of a PV by optimization techniques is relatively complex because the characteristic of the cells is highly dependent on solar irradiation and ambient temperature. In recent years, several MPPT methods have been published [7], [21]-[25]. Among these methods is the P&O algorithm (Perturb and Observe). This method is based on the principle of a small amplitude voltage disturbance v_{pv} of its initial value, which directly influences the duty cycle of the PV's DC-DC converter. This method is described by the flowchart shown in Fig. 4.

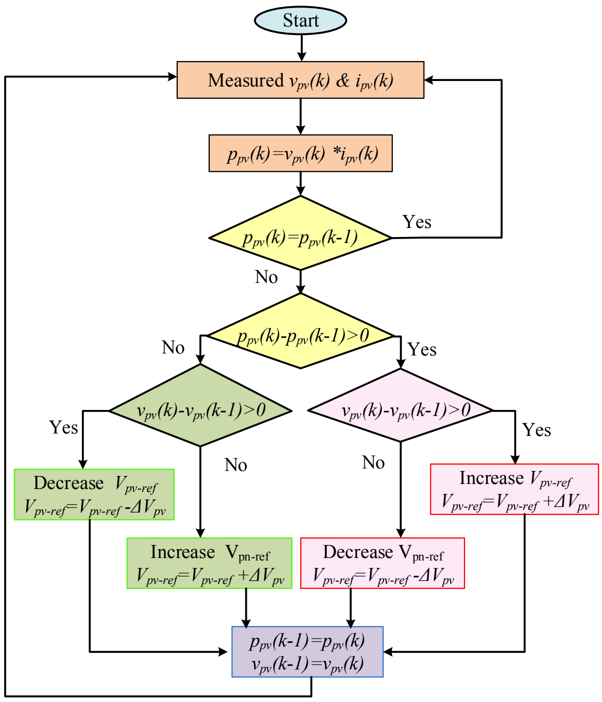

Fig. 4. P&O method for the MPPT [25]

As illustrated in Fig. 3, after setting the reference value of the v_{pv} by MPPT algorithm, the PV converter control system is generated through a PI controller and a PWM block. To determine the controller parameters by using average modeling for each part of the system, a transfer function is defined. Then, the controller parameters are found through Bode diagram of the closed loop control.

V. Simulation Results Based on a Residential Load Profile

In this section, simulation results are provided to verify the validity of the proposed energy management approach. The system is emulated under MATLAB-SimPowerSystems environment. The system parameters are given in Table 1.

TABLE 1
SYSTEM PARAMETERS

Ultra Capacitor	L_{UC}	2mH
	R_{UC}	0.5Ω
	C_{UC}	165F
	R_{UCS}	3.85mΩ
	R_{UCS}	100kΩ
Photovoltaic	L_{PV}	9mH
	R_{PV}	0.8Ω
	C_{PV}	40mF
	Number of PV panels	3(serie)*6(parallel)
Battery	L_{bat}	2mH
	R_{bat}	0.7Ω
	V_{emf}	20.15V
	R_1	94.2Ω
	R_2	73.6mΩ
	C_b	4581F
	Number of batteries	4

First, the PV modeling and the MPPT algorithm performances are validated. Fig. 5 shows the *P-V* and *I-V* characteristics of the modeled PV with different solar irradiation. The obtained results correspond to the BP 3170 photovoltaic module of the BP solar company. P&O MPPT is applied to a 170W module; and the obtained PV module voltage and output power can be seen in Fig. 6. In this example, the solar irradiation is 1000W/m2 and the temperature is 25°C. As this figure shows, the algorithm is initiated at 31V and progressively converges towards the power peak. Once the Maximum power point (MPP) is attained, the V_{pv} oscillates around the MPP voltage.

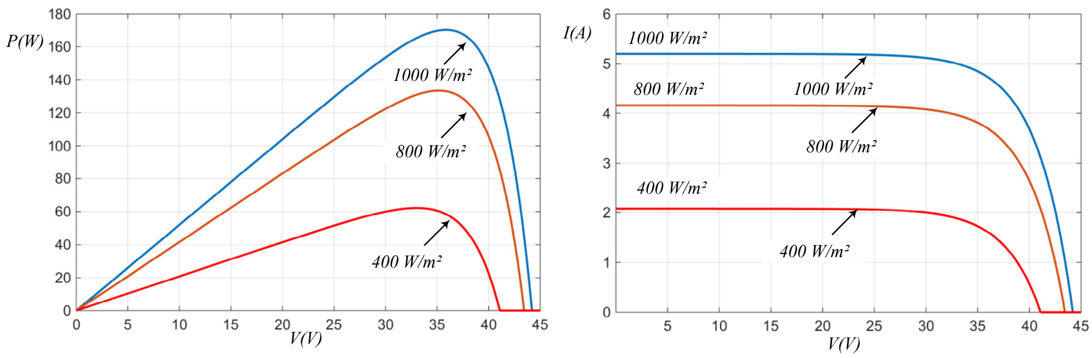

Fig. 5. (Right) P-V (Left) I-V output characteristics with different solar irradiations

Secondly, to validate the proposed energy management strategy for the studied microgrid, the DC bus voltage reference is fixed to 200V. The implemented profile of the residential load is focused on the summer season as it is presented in the first curve (i_{load}) of Fig. 7. This figure presents the hourly average power consumption by domestic appliances during 24 hours. DC bus voltage is presented in the top of Fig. 8. It is the same as the reference voltage regardless of the load's variations.

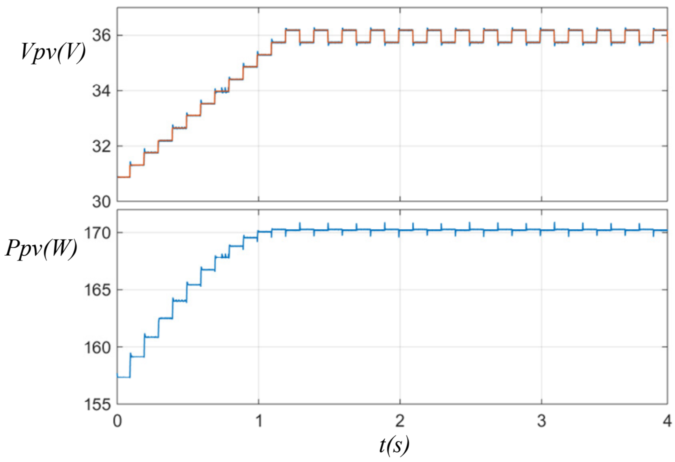

Fig. 6. Evaluation of P&O MPPT voltage and power

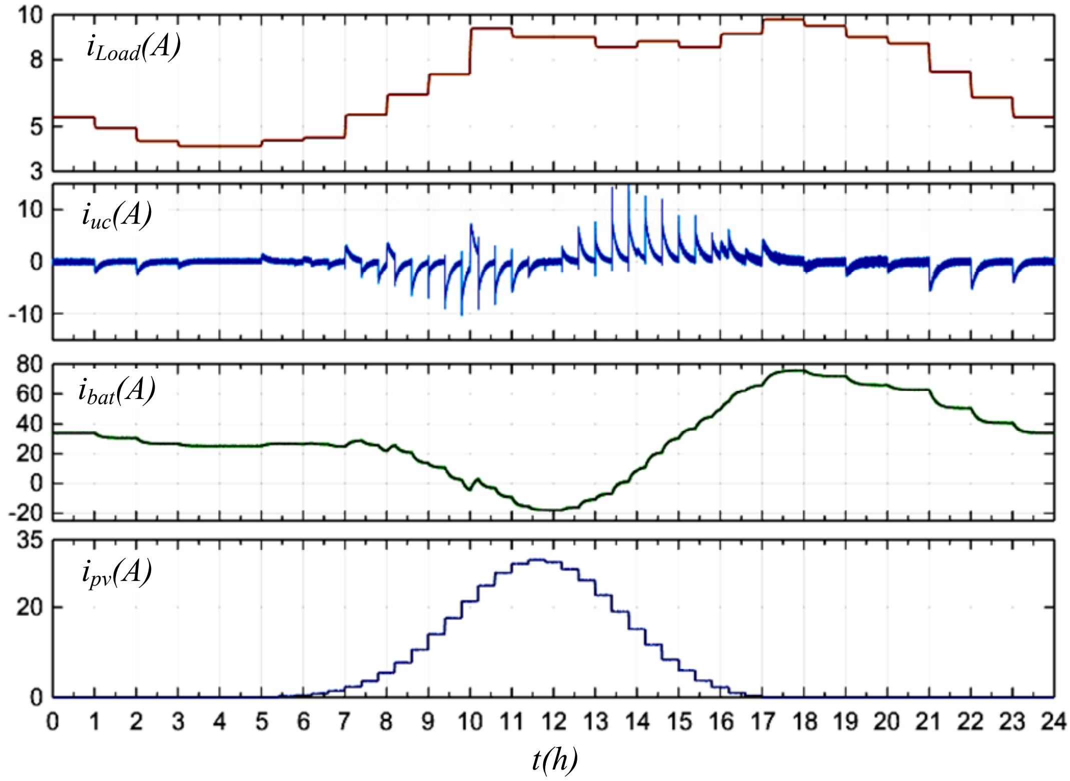

Fig. 7. From up to down: summer residential load profile, UC, battery pack and PV current

In reality, the daily solar irradiation has the general shape of a curve called "bell", which is modeled here by a Gaussian curve of (8). That is why the PV panel current is null from 17h00 to 6h00 in Fig.7. Out of this time interval, the PV provides the possible maximum power and supplies the DC bus as shown in Fig.9. Corresponding to solar energy variation, P_{max} of PV has been also varied. As Fig. 8 illustrates, the MPPT algorithm increases progressively V_{pv} and converges towards the MPP voltage to achieve the power peak.

$$G(t) = 1000 \times e^{-\left(\frac{(t-12)^2}{8}\right)} \tag{8}$$

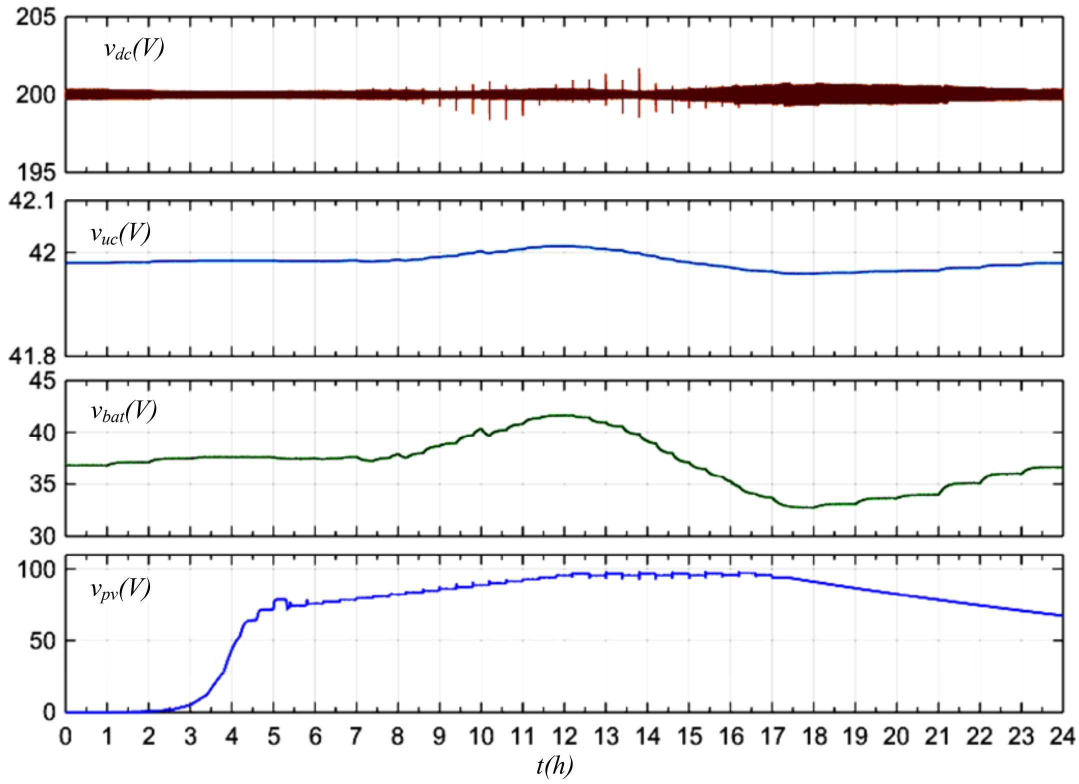

Fig. 8. From up to down: DC-bus, UC, battery pack and PV voltage

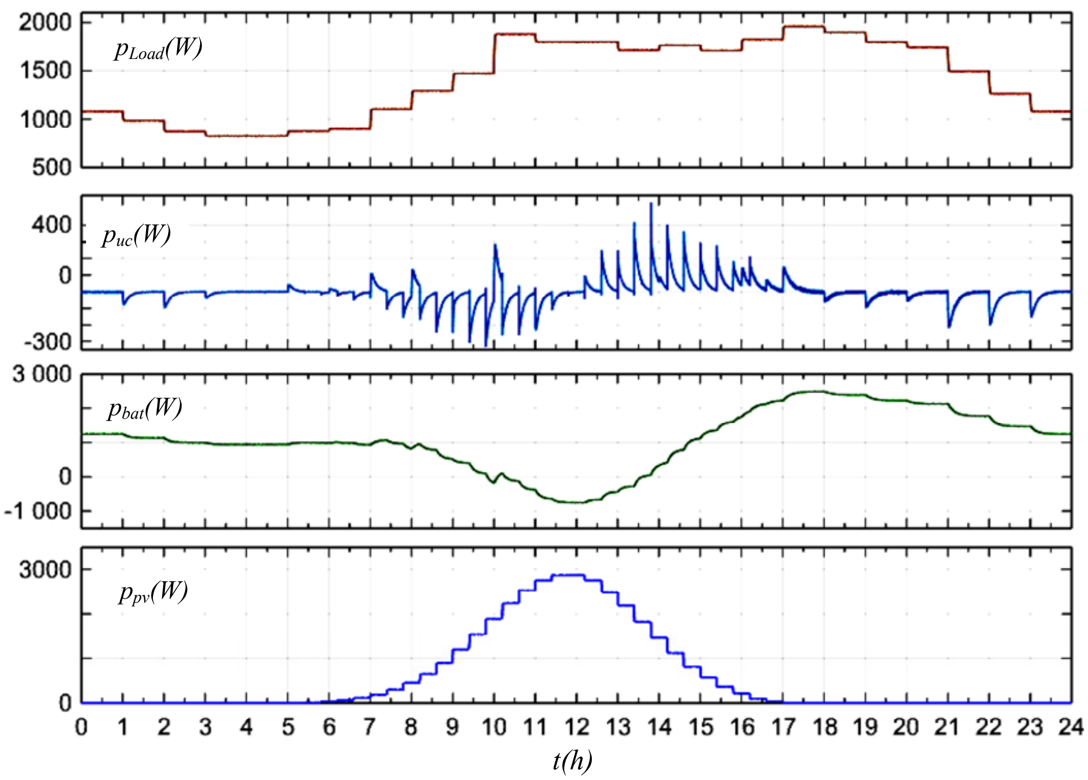

Fig. 9. From up to down: power of load, DC-bus, UC, battery pack and PV

As it has been already mentioned, the UC is responsible for the rapid load and PV energy variations. Fig. 7 shows that, the UC current perfectly compensated the rapid variation either from the load profile or from the PV. This action of the UC allows having a constant DC bus voltage. The battery pack which has a slower dynamic compared to the UC supplies or

absorbs the required energy to smooth the difference between the PV produced power and load demand in longer time, as shown in Fig. 7 and Fig. 9. From 10h00 to 14h00, the PV production is more than the load demand; thus, the battery absorbs and stocks energy. That is why the i_{bat} and P_{bat} are negative in this time interval (in Fig. 7 and Fig. 9). The battery also controls the UC voltage around its nominal voltage (see Fig. 8).
Finally, the simulation results show the performances of the proposed energy management approach. The DC bus voltage is fixed at its reference; the PV maximum power is extracted; and the UC is perfectly replayed to rapid energy variations.

VI. CONCLUSION

This paper presents the energy management in a stand-alone DC microgrid. The studied system consists of a photovoltaic as a main renewable energy source. In order to smooth the load and PV production variations, an ultra capacitor and a battery pack are used. The UC, due to its rapid dynamic, is responsible for regulating DC bus voltage during fast power variations. The battery pack compensates the difference between PV production and load demanded power in the long term. An energy management based on energy balance on DC bus capacitor is proposed in this paper. Proportional-Integral controllers are used in order to control the system and achieve energy management objectives. Finally, the performances of the proposed method are validated by simulations.

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