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Application of Petri nets for the energy management of a photovoltaic based power station including storage units

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ABSTRACT

This paper deals with the energy management of a photovoltaic based power station. This power station includes storage units with batteries for long-term energy supply and ultracapacitors for fast dynamic power regulation. According to the availability of the primary source, the level of the stored energy and the request from the grid operator, we have defined and detailed three main operating modes for this system with a particular modeling tool: Petri nets. For each operating mode, we have designed an energy management algorithm in order to calculate the energy dispatching of an adjustable power margin for the storage units.

1. Introduction

In recent years, more and more renewable energy based generators have been used in the electrical power system. The purpose is to get a cleaner electrical power generation.

The renewable energy based generators (photovoltaic panels, wind turbines…) have a random electric production, which is directly dependent upon the weather conditions (wind speed, illumination, temperature…). Consequently, the adequacy between the required power (for the consumers) and the electrical PV production must be provided by conventional generators. Actually this compensation power is given by the fossil based generators. In islanded electrical networks and microgrids this situation is more critical as fossil based generator have a limited power capacity. Therefore, the development of renewable energy based generators is quite naturally limited with a penetration ratio of about 30%.

One possible solution is to add an embedded storage unit in the renewable energy based generator in order to satisfy new grid requirements (power dispatching, ancillary services…). Storage systems can balance the variations of the renewable production and also can help to provide a timing power reference, which is asked by the grid operator. In the past a first energy system has been implemented with a flywheel storage system [1–3]. A supervision strategy for the local power flow enables a smooth generated power.

In this paper the objective for the renewable energy based generator is to provide real and reactive powers, which correspond to the power references (P_{g_ref}, Q_{g_ref}) coming from a grid operator (Fig. 1) [4]. Hence we assume that a commercial contract exists between the producers and the grid operator for a daily power planning. In order to ensure the power availability during cloudy days and during a part of the night, a long-term energy storage is required as batteries, hydrogen chain, compressed air system … The recent studies have shown that it is not necessary to consider a storage capacity higher than 2 or 3 days autonomy [5,6]. We have chosen to use two different storage units; Lead-acid batteries for providing the long-term electrical energy and ultracapacitors for the fast dynamic power regulation [7,8]. For protecting constraints, batteries must be charged or discharged with an optimal power tracking in order to avoid overcharges and discharges. Because of this battery protecting use, ultracapacitors are used to compensate in real time the PV production in order to provide the grid power references. Ultracapacitors cannot be used alone because the sizing for the required energy would very large and the cost will be too expensive [8,9]. So, here, ultracapacitor power is sized only for providing the necessary transient power. In this paper we detail the design of the local energy management for a multisource power station within 3 kW photovoltaic panels, 10 kWh lead-acid batteries

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Nomenclature

p_{pv}	the produced power by the PV panels
P_g	the generated real power to the grid
p_{bat}	the exchanged power with the batteries
Q_g	the generated reactive power to the grid
p_{uc}	the exchanged power with the ultracapacitors
p_{pv_MPPT}	the maximum power from the PV panels in MPPT
p_{sto}	the exchanged power with all storage units
p_{DC}	the exchanged power with the DC bus
p_{AC}	the power issued from the inverter
p_{conv}	the total DC power from PV panels and storage units
u_{pv}	the voltage across the PV panels
i_{pv}	the current from the PV panels
u_{bat}	the voltage across the batteries
i_{bat}	the current from the batteries
u_{uc}	the voltage across the ultracapacitors
i_{uc}	the current from the ultracapacitors
u_{DC}	the DC common bus voltage
i_{DC}	the current in the DC bus capacitor
$\underline{v_s}$	the three-phase grid voltage vector
$\underline{i_s}$	the three-phase grid current vector
L_1	the inductor of the PV filter
L_2	the inductor of the battery filter
L_3	the inductor of the ultracapacitor filter
L_4	the inductor of the grid filter

for long-term power storage and 36 kW min ultracapacitors for fast dynamic power regulation (Fig. 1).

Firstly we present the structure of this photovoltaic based multisource power station. Then the concept of the hierarchical control is introduced. The hybrid modeling of the entire power station is presented and depicted with Petri nets [10]. The power tracking system is designed and three operating modes of the power station are defined. For each mode, the management system carries out the calculation and the energy dispatching within the storage units of a variable power margin. We use also a Petri net for the decision of operating modes.

2. Structure of the multisource power station

The photovoltaic panels, the batteries and the ultracapacitors are connected to a common DC voltage bus through their dedicated DC/DC chopper (Fig. 1). The grid connection is performed by a three-phase inverter. The 3 kW peak power photovoltaic power station is made up of 18 BP Solar 3160 panels. The 10 kWh energy lead-acid batteries hold a 144 V voltage (12 cells in series). In comparison with the batteries, the ultracapacitors have a lower capacity of energy storage but a higher density of peak power. The main application of the ultracapacitors is to use them as fast dynamic energy buffers. The use of ultracapacitors requires power electronic converters in order to offer an efficient management of the storage level. The management of their energy levels is a significant point because ultracapacitors are often connected with several sources of energy. For our application, ultracapacitors are used not only to smooth the variations of the PV power but also to give a real time power regulation in respond to the grid operator demand. They make the whole power station more dynamic.

3. Modeling of source states with Petri nets

3.1. Storage units

Each unit of the active generator (the batteries, the ultracapacitors, the photovoltaic panels) is modeled with a Petri net as

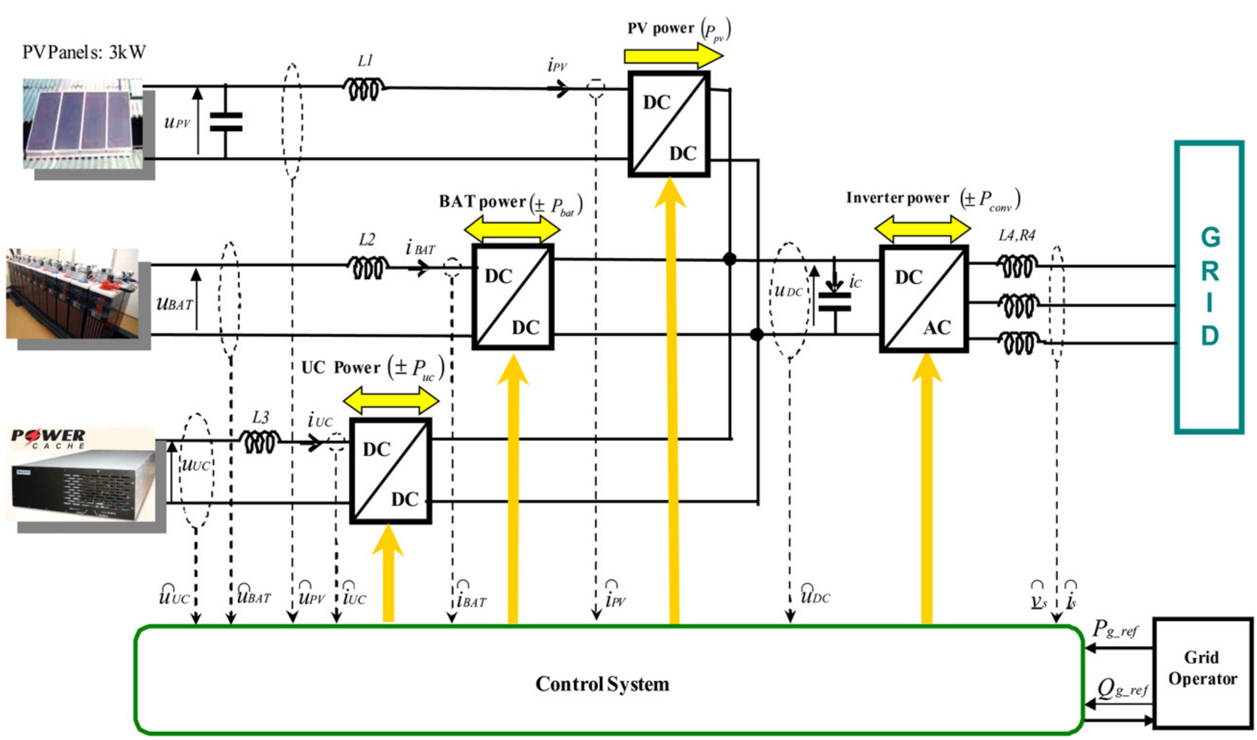

Fig. 1. Grid-connected photovoltaic power station including batteries and ultracapacitors.

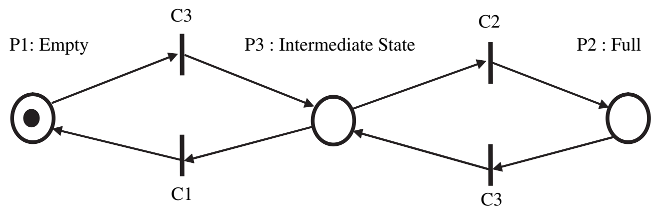

Fig. 2. Modeling with Petri nets of batteries or ultracapacitors.

well as the connection to the grid. As example three states for the batteries are considered (Fig. 2) and are represented on the Petri net by three places (P1, P2, P3) and three conditions (C1, C2, C3). For the first place (P1), the battery is empty and this state is reached when its SOC (State Of Charge) becomes equal or inferior to a minimum value. This condition is expressed as:

C1 $SO\tilde{C}bat \leq SOCbat\_min$

$SO\tilde{C}bat$ is the estimated value of the state of charge.

For the second place (P2), the battery is fully charged and this state is reached when its SOC becomes equal or higher to a maximum value:

C2 $SO\tilde{C}bat \geq SOCbat\_max$

For the third place (P3), the battery is in an intermediate state if remaining conditions are satisfied:

C3 $SOCbat\_min < SO\tilde{C}bat < SOCbat\_max$

At any time, the state of the battery is shown by a place with a token in Petri nets. Hence the state can be mathematically expressed by a variable with three values $E_{bat} \in$ {P1, P2, P3}.

The same Petri net can be used to model the ultracapacitors but conditions (C1, C2, C3) have to be modified to take into account the ultracapacitor voltage. The SOC of the ultracapacitor is assumed to be linear with the squared ultracapacitor voltage. And so we obtain the possible states for the ultracapacitor: $E_{uc} \in$ {P1, P2, P3}

3.2. PV panels

Two states are used to model PV panels. Photovoltaic panels can work in the well known MPPT mode (place P1 on Fig. 3) or in a power limitation mode (place P2 on Fig. 3) when more power are available than required by the grid operator. The maximum PV power is estimated thanks to continuous monitored weather data [11].

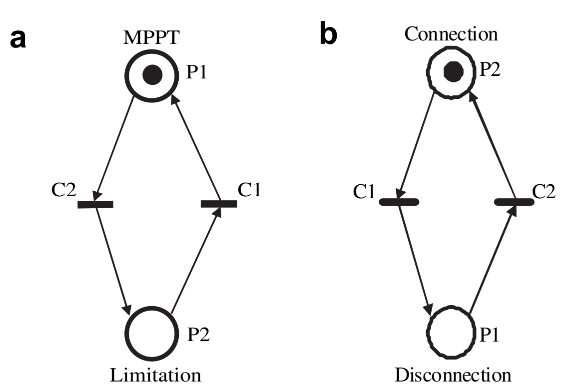

Fig. 3. Modeling of the photovoltaic panels (a) and the grid connection (b).

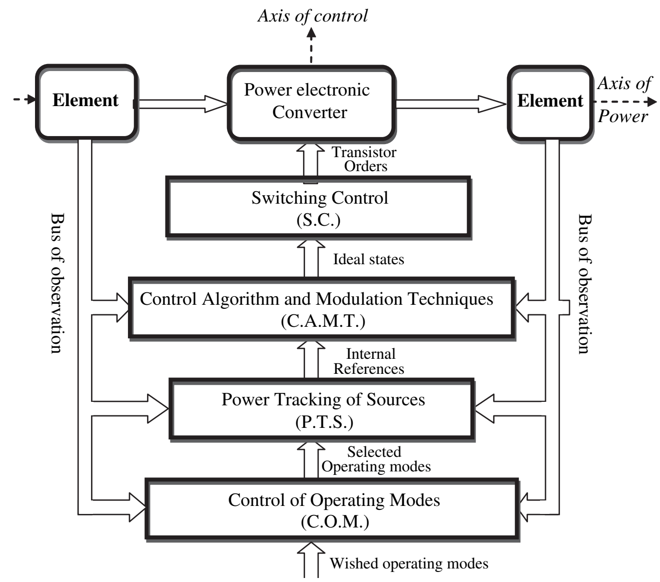

Fig. 4. Structure of the hierarchical control.

In an MPPT mode two situations may occur. In the first one the maximum power from PV is required for the grid. In this case the estimated maximum PV power ($\tilde{P}_{PV\_MPPT}$) is less than the required reference power (P_{CONV_ref}). In the second one, a part of the PV power is not useful for the grid and is stored in embedded storage units. The availability of storage units can be evaluated through the battery SOC ($SO\tilde{C}bat$) and the ultracapacitor voltage (u_{uc}). Batteries and ultracapacitors are available if respectively the estimated battery SOC and the sensed voltage across the ultracapacitor are less than their maximum value. These conditions are gathered as:

C1 $\left(\tilde{P}_{PV\_MPPT} < P_{CONV\_ref}\right)$ OR $\left(SO\tilde{C}bat < SOC\max\right)$ OR

$(u_{uc} < u_{uc\_min})$.

The limitation mode of PV panels (place P2) must be used if the PV power is higher than the required power reference and the storage units are fully loaded and so unavailable.

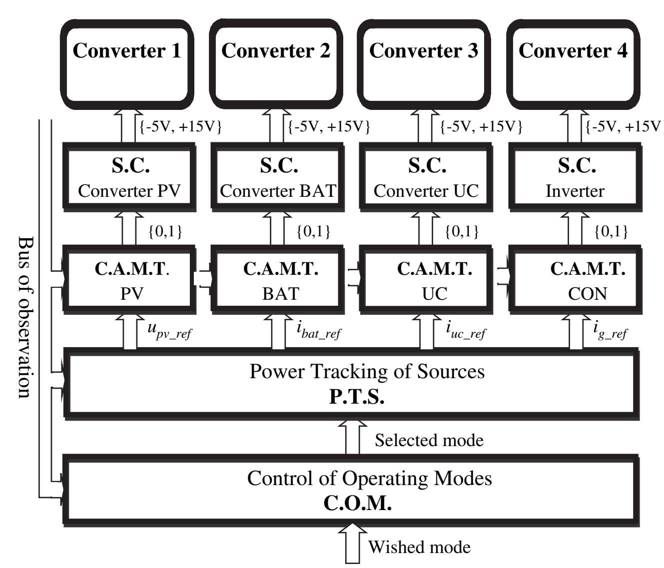

Fig. 5. Application of the hierarchical control.

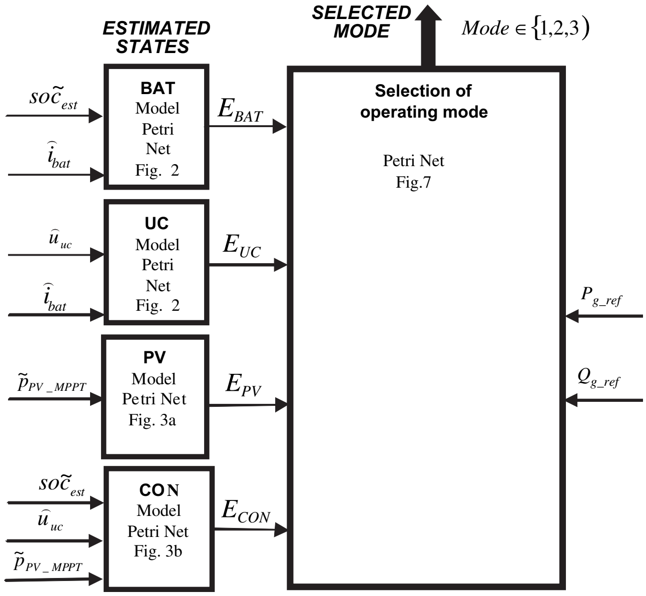

Fig. 6. Control of Operating Modes: COM.

C2 $\left(\tilde{P}_{\text{PV\_MPPT}} > P_{\text{CONV\_ref}}\right)$ AND $\left(SO\tilde{C}bat \geq SOC\text{max}\right)$

AND $(u_{\text{uc}} \geq u_{\text{uc\_max}})$.

3.3. Grid connection

To describe the connection with the grid, we have also defined two states. The first place (P1) on Fig. 3b corresponds to the disconnection of the active generator from the grid. When the PV production is smaller than the required grid power and the storage units are fully discharged, the priority is given to charge the storage units in order to make available as soon as possible the power station in a safety operation.

C1 $\left(\tilde{P}_{\text{PV\_MPPT}} < P_{\text{CONV\_ref}}\right)$ AND $(SO\tilde{C}bat \leq SOC\text{min})$

AND $(u_{\text{uc}} \leq u_{\text{uc\_min}})$.

In the same time, information about the "off" state of the power station is sent to the grid operator. Hence the grid operator can use other power sources, which are more interesting (from the technical and economical point of view). This strategy is used in order to guarantee a sufficient power margin when this PV based power station is connected.

The second state (P2) corresponds to the grid connection and is achieved when the batteries and the ultracapacitors are fully charged.

C2 $(SOCbat \geq SOC\text{max})$ AND $(u_{\text{uc}} \geq u_{\text{uc\_max}})$.

The state of photovoltaic panels and the state of the grid connection are respectively represented by a token inside one place and so we get;$E_{\text{PV}} \in \{\text{P1,P2}\}$ and $E_{\text{CON}} \in \{\text{P1,P2}\}$.

Table 1
Tests for the selection of an operating mode.

Conditions			Selected mode
$P_{\text{PV\_MPPT}}$	E_{BAT}	E_{UC}	
	P3	P3	N°1 Normal
$>P_{\text{conv\_ref}}$	P2	P2	N°2 Limitation
$<P_{\text{conv\_ref}}$	P1	P1	N°3 Stand alone

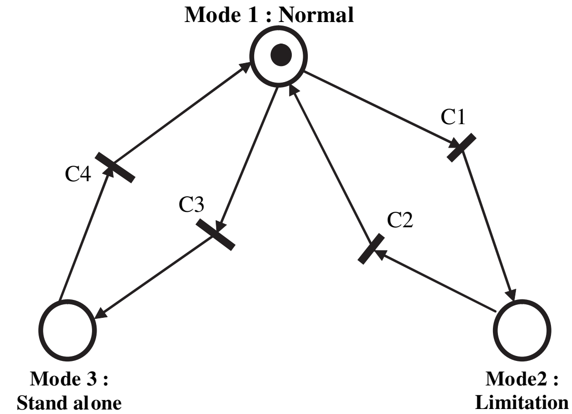

Fig. 7. Petri nets for the selection of operating modes.

4. Hierarchical control

A hierarchical control has been used for the design of the energy management system [12]. The structure of a hierarchical control system for a power electronic converter includes 4 levels (Fig. 4).

Each one has precise control tasks depending on its hierarchical position:

- Control of Operating Modes (COM),
- Power Tracking of Sources (PTS),
- Control Algorithms and Modulation Techniques (CAMT),
- Switching Control (SC).

The switching control calculates the transistor signals ($\{-5, +15\}$) in order to set reference ideal states of the semiconductor ($\{0, 1\}$).

The active generator has four power converters and thus we have also four SC and four CAMT, which are dedicated for each converter (Fig. 5). The PTS generates the different reference signals. The COM must control each unit according to the different operating modes of the whole active generator.

5. Design of the COM

The COM has 2 parts (Fig. 6). The first part estimates the state of each source and uses the previous presented Petri net modeling of sources. The second part selects operating modes of the power station.

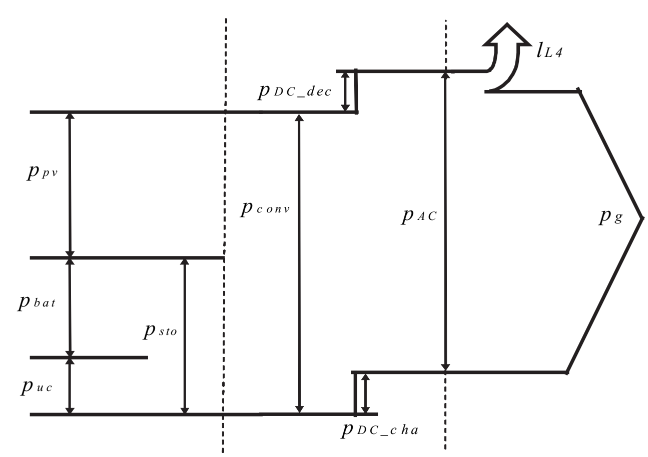

Fig. 8. Power flow in the normal mode.

Table 2
Modeling and management equations of the power flow in the normal mode.

Modeling equations		Power management	
$p_{sto} = p_{bat} + p_{uc}$	(6)	$p_{bat\_ref} = f(p_{sto\_ref})$ $p_{uc\_ref} = p_{sto\_ref} - p_{bat\_ref}$	R1c
$p_{conv} = p_{pv} + p_{sto}$	(7)	$p_{sto\_ref} = p_{conv\_ref} - \widehat{p}_{pv}$	R2c
$p_{AC} = p_{conv} - p_{DC}$	(8)	$p_{conv\_ref} = p_{AC\_ref} + p_{DC\_ref}$	R3c
$p_g = p_{AC} - l_{L4}$	(9)	$p_{AC\_ref} = p_{g\_ref} + \tilde{l}_{L4}$	R4c

According to the state and availability of each source (PV, ultracapacitors, batteries, connection to the grid), several operating modes of the entire power station can be implemented. The states of each element (E_{BAT}, E_{UC}, E_{PV} and E_{CON}) are determined by the presented Petri nets in part 3. The selection process chooses an operating mode for the power station according to these states and the requirement of the grid operator (Fig. 5). Three main modes are now detailed.

5.1. Mode N°1 (normal mode)

For this mode the photovoltaic panels can work in MPPT and the batteries and ultracapacitors are available (Table 1). The power station is connected to the grid and the inverter delivers the electric power to meet grid power references. If the produced electric power from PV panels is more or less than power references of the grid, the batteries and the ultracapacitors can be used to compensate this difference. So the mode N°1 is characterized by a medium state of charge (SOC) of batteries and ultracapacitors (Table 1). When the *SOC_bat* of battery is between *SOC*min and *SOC*max, and the voltage across the ultracapacitors is between U_{uc_min} and U_{uc_max}, the COM asks the photovoltaic panels to work in MPPT by setting the mode parameter to be equal to 1.

5.2. Mode N°2 (limitation mode)

In the mode 2, the available power from the photovoltaic panels is more than the required power reference from the grid. To detect this situation the theoretical maximum produced PV power in MPPT (P_{pv_MPPT}) must be estimated and compared with the power reference set point (P_{conv_ref}). Moreover for this mode the batteries and the ultracapacitors are fully charged and the grid is connected (Table 1). So the battery state of charge may outstrip the maximum *SOC* and the storage level of ultracapacitors can overcome the maximum level U_{uc_max}. Hence, we must limit the produced power from the PV panels.

5.3. Mode N°3 (stand alone mode)

In this mode, the PV panels work in MPPT but the primary source is very low and the batteries and the ultracapacitors are empty. The produced power is not supplied to the grid because it is not enough for the grid. The grid is disconnected and the batteries and ultracapacitors are charged.

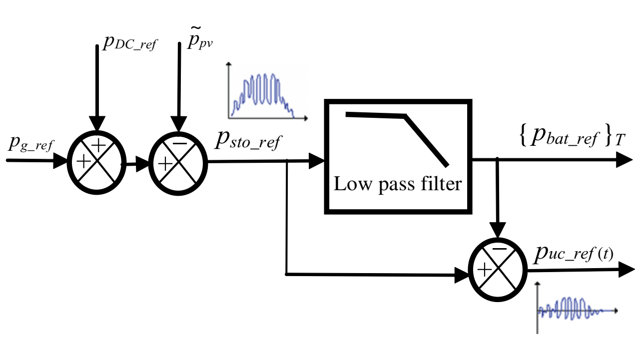

Fig. 9. Schema block representation of the power dispatching.

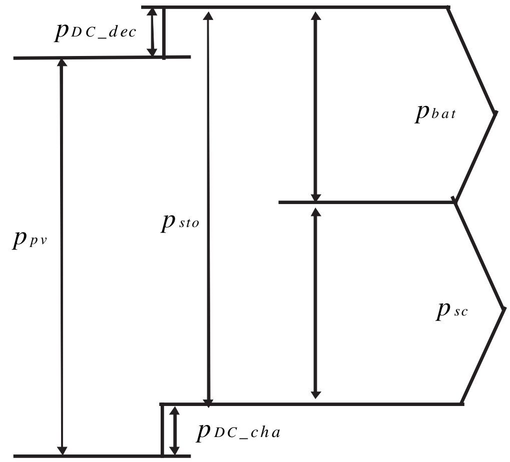

Fig. 10. Power flow in stand alone mode.

The selection of the operating mode has been implemented by a Petri net (Fig. 7) whose different conditions for the passage from one mode to another one are expressed as:

C1 $(E_{BAT} = P_2)$ AND $(E_{UC} = P_2)$ AND $(E_{PV} = P_2)$ AND $(E_{CON} = P_1)$

C2 $(E_{BAT} = P_3)$ AND $(E_{UC} = P_3)$ AND $(E_{PV} = P_1)$ AND $(E_{CON} = P_1)$

C3 $(E_{BAT} = P_1)$ AND $(E_{UC} = P_1)$ AND $(E_{PV} = P_1)$ AND $(E_{CON} = P_2)$

C4 $(E_{BAT} = P_2)$ AND $(E_{UC} = P_2)$ AND $(E_{PV} = P_1)$ AND $(E_{CON} = P_1)$

6. Design of the PTS

We detail now the PTS for the three presented main modes of the hybrid power station. According to the selected mode, the PTS has to calculate the power references for each CAMT of units (Fig. 5).

6.1. Mode N°1: normal mode

When the normal mode is selected, the photovoltaic panels are working in MPPT with a particular algorithm [13]:

$$p_{pv\_ref} = f_{MPPT}\left(\widehat{i}_{pv}\right) \quad (1)$$

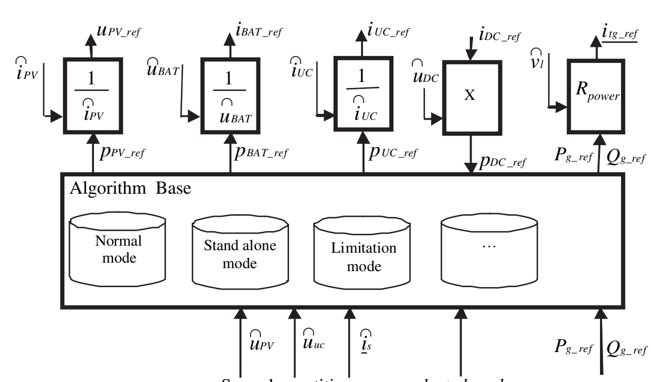

Fig. 11. Algorithms for the PTS.

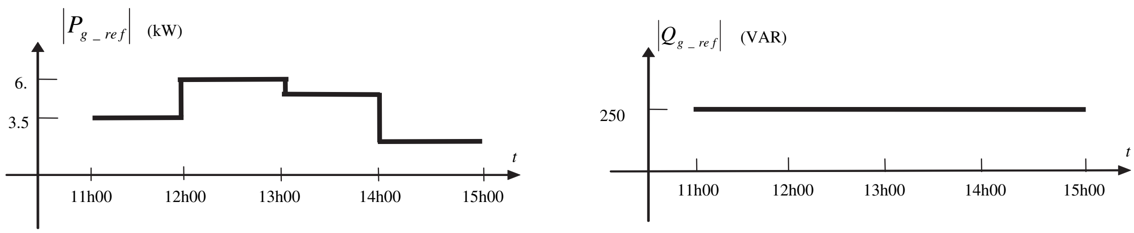

Fig. 12. Power references for the power station.

For the theoretical analysis, we assume that the batteries and the ultracapacitors are in generating mode. The power flow from sources to the grid is described in Fig. 8.

The total exchanged power with both storage units is calledp_{sto}. The exchanged power with the capacitor of the DC bus is calledp_{DC}:

$$p_{DC} = i_c \cdot u_{DC} \tag{2}$$

On Fig. 8, this power is decomposed into two terms: p_{DC_cha}if the capacitor is loaded ($p_{DC} = p_{DC\_cha} < 0$) and p_{DC_dec}if the capacitor is unloaded ($p_{DC} = p_{DC\_dec} > 0$). Modeling equations of the power flow are summarized in Table 2.

The purpose of the PTS is to calculate the power dispatching among the storage units, the PV generator and the generated grid power (p_g) in order to generate a prescribed power references (p_{g_ref}). The losses in the grid filter can be estimated with the sensed grid currents ($\widehat{i_s}$):

$$\tilde{i}_{L4} = 3 \cdot R \cdot \widehat{i_s} \tag{3}$$

They are used to calculate the total AC power reference (p_{AC_ref}), which must be supplied by the grid power electronic inverter (control equation R4c in Table 2). A part of this power is required to regulate the DC bus (p_{DC_ref}) and is calculated by using a measurement of the DC bus voltage ($\widehat{u}_{DC}$) and the current reference (i_{c_ref}):

$$p_{DC\_ref} = \widehat{u}_{DC} \cdot i_{c\_ref} \tag{4}$$

This power reference is taken into account in the power flow management (R3c) (Table 2). The reference of the exchanged power with both storage units is calculated by using an estimation of the produced PV power (R2c). As batteries have low transient dynamics, a low pass filter is used to calculate the battery power reference (R1c). The missed power is a fast transient quantity and can be easily calculated [14,15]. It is used as the power reference for the ultracapacitors (R1c) (Fig. 9).

6.2. Mode N°2: limitation

In this operating mode, the *SOC* (State Of Charge) of the batteries is larger than the *SOC*max and the voltage across the ultracapacitors is larger than U_{uc_max}. Hence storage units have to be setup in stand by:

$$p_{sto\_ref} = p_{bat\_ref} = p_{uc\_ref} = 0 \tag{5}$$

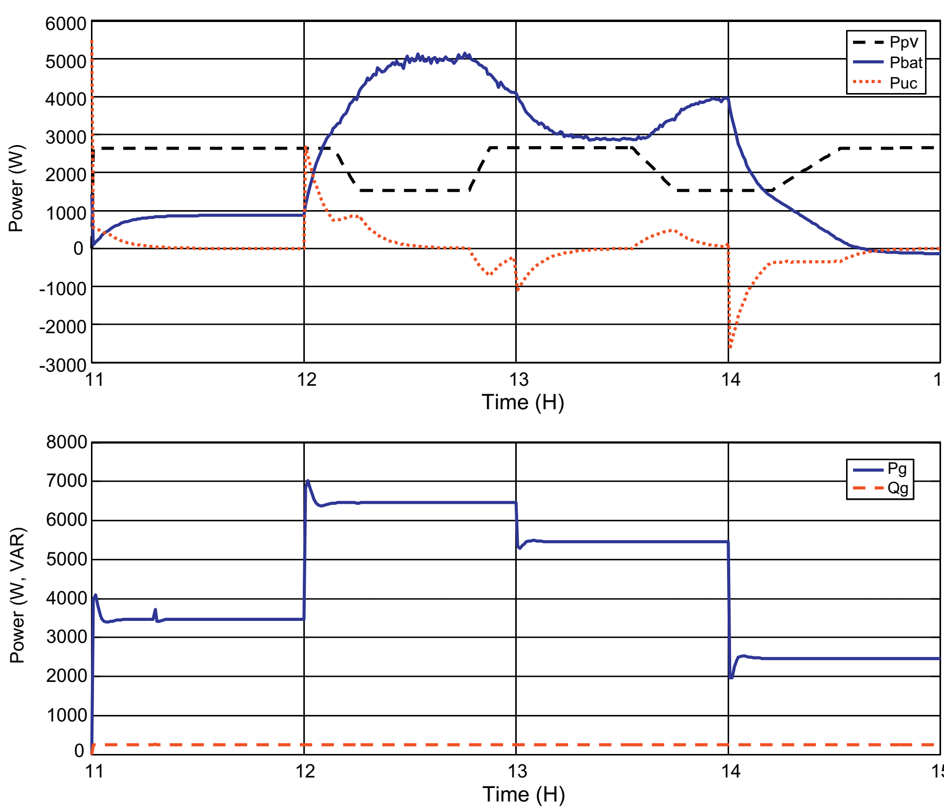

Fig. 13. Simulation results in the normal mode.

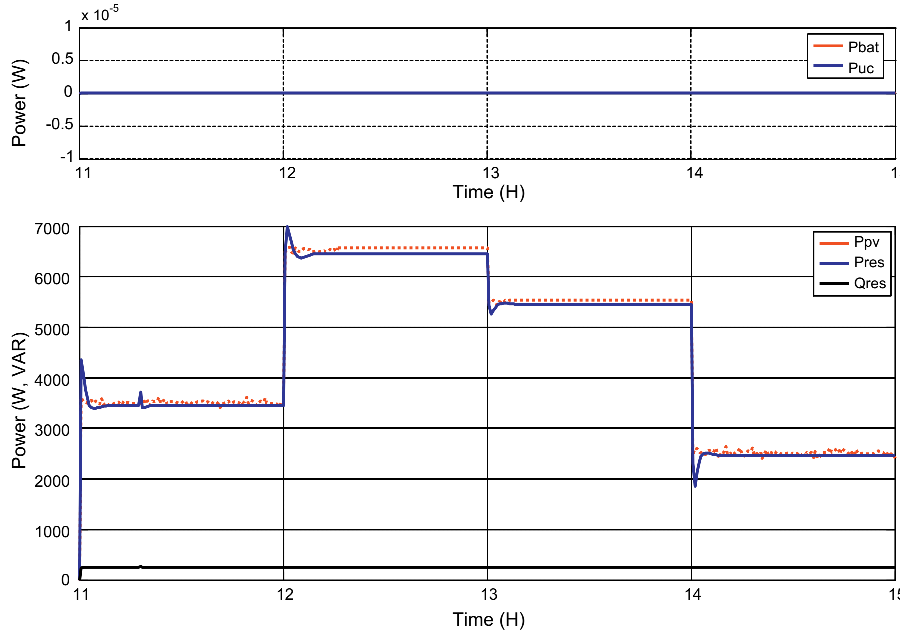

Fig. 14. Simulation results in the limitation mode.

Moreover for this operating mode the obtained power in mode MPPT from the photovoltaic panels is higher than the required power P_{conv_ref}[14]. The PV power cannot be sent to the grid. Therefore, we must limit the power production of the PV panels. They should not produce more power than the prescribed set point (p_{conv_ref}):

$$p_{pv\_ref} = p_{conv\_ref} \quad (6)$$

6.3. Mode N°3: stand alone

In the stand alone mode, the grid is disconnected, hence we must set:

$$p_{g\_ref} = 0.$$

The photovoltaic panels can work in MPPT. Hence, we charge the ultracapacitors until that the sensed voltage across the ultracapacitors $(\widehat{u}_{uc})$ is equal to the nominal voltage of operation (U_{uc_nom}). As the grid power is null and we must control the DC bus voltage, the power dispatching is simplified (Fig. 10):

$$p_{sto\_ref} = \widehat{p}_{PV} + p_{DC\_ref} \quad (7)$$

Then, the batteries and the ultracapacitors are simultaneously loaded.

In the PTS level (Fig. 11), one algorithm is executed and calculates power references (e.g. Table 2) according to the selected operating mode and the measured quantities. Then these power references are transformed to current or voltage references for control algorithms in the CAMT level (Fig. 4).

7. Simulation results

Fig. 12 shows the studied power production plan, which has been given by the grid operator.

7.1. Mode 1: normal mode

In Fig. 12, at 12 o'clock, the power, which is required by the grid, increases very quickly to 6 kW according to the power production plan. The generated power by the PV panels (P_{pv}) is about 2.7 kW and is not sufficient (Fig. 13). The batteries cannot provide all the

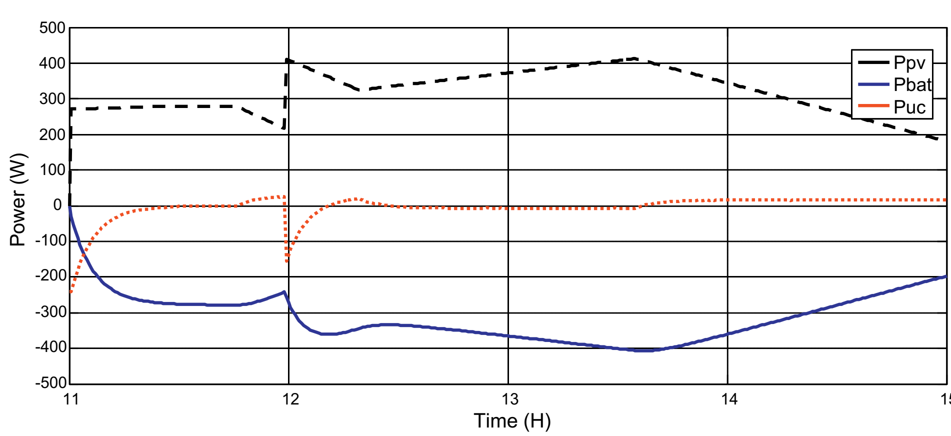

Fig. 15. Simulation results in stand alone mode.

missing power because the batteries have low dynamics. We show that the ultracapacitors are well used to compensate the gap. Unless the fluctuations of the produced PV power, we can see a good coordination of both storage units. The generated power (P_g, Q_g) meets the requested reference (P_{g_ref}, Figs. 12 and 13).

7.2. Mode 2: limitation mode

In this experimental test, the weather is very sunny. In Fig. 14, we can see that the generated power by the PV panels can strictly follow the grid reference. But the surplus power cannot be injected into storage units, which are already fully charged. Thus the exchanged power with batteries and ultracapacitors is null and we can see that the PV panels are controlled in a dynamic limitation mode.

7.3. Mode 3: stand alone mode

In this experimental test, the weather is very cloudy. The generated power by the photovoltaic panels is insufficient. In Fig. 14, we can see that the batteries are charged with the available PV power. Supercapacitors are used to limit the battery current during the starting and to filter the PV power fluctuations (Fig. 15).

8. Conclusion

In this paper, an energy management system for a photovoltaic based power station including storage units has been introduced. We have described states of each source in the power station with Petri nets. Several different levels of the control system have been identified and organized in a hierarchical control structure. They have been implemented through this power management system. The three main operating modes of the entire power station have been presented. According to the states of the three sources, the energy management system chooses the corresponding operating mode and calculates the power reference of each source. The planning of the electric power supply has been agreed in the form of real and reactive power reference. A general control strategy has been developed with the tool "Petri nets". Other operating modes, which correspond to faulty conditions, can be considered to complete the whole energy management.

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