Energy Management and Operational Planning of a Microgrid With a PV-Based Active Generator for Smart Grid Applications

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***Abstract*—The development of energy management tools for next-generation PhotoVoltaic (PV) installations, including storage units, provides flexibility to distribution system operators. In this paper, the aggregation and implementation of these determinist energy management methods for business customers in a microgrid power system are presented. This paper proposes a determinist energy management system for a microgrid, including advanced PV generators with embedded storage units and a gas microturbine. The system is organized according to different functions and is implemented in two parts: a central energy management of the microgrid and a local power management at the customer side. The power planning is designed according to the prediction for PV power production and the load forecasting. The central and local management systems exchange data and order through a communication network. According to received grid power references, additional functions are also designed to manage locally the power flows between the various sources. Application to the case of a hybrid supercapacitor battery-based PV active generator is presented.**

***Index Terms*—Energy management, load forecasting, microgrid, operational planning, renewable energy prediction, smart grids, sustainable energy.**

I. Introduction

THE need to reduce pollutant gas emissions and the liberalization of the electricity market have led to a large-scale development of distributed renewable energy generators in electrical grids [1]. Nowadays, renewable energy generators, such as photovoltaic or wind power generators, are used to reduce fuel consumption and greenhouse gas emissions. However, the output power fluctuation of renewable energies may cause excess variations of the grid's voltage and frequency. In recent years, storage systems have been used to design active generators, which are able to provide an energy reserve with a less fluctuating output power [2]–[4]. As an example, Fig. 1 shows a home application with PhotoVoltaic (PV) panels and a demand response capability via some controllable loads and storage units. During the day, this home application may be a power producer or a consumer—also known as a "prosumer."

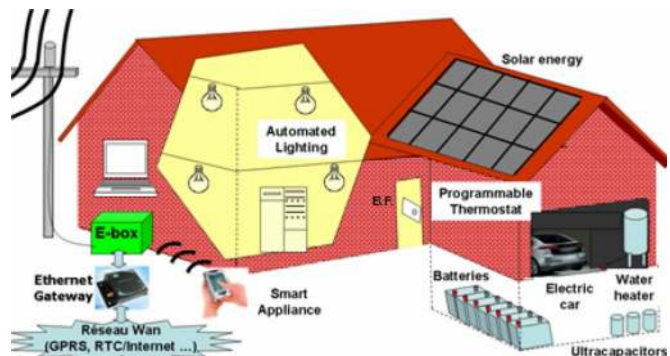

Fig. 1. Prosumer with load demand response and production capabilities.

A few years ago, energy boxes (E-boxes) were developed in order to follow energy consumption [5]. They have been upgraded to increase consumer satisfaction with the option for automatic control of some loads.

Customer-enabled management provides opportunities for consumption adaptation to time pricing and new grid services for higher quality power supply (Yellow Strom's meter, Linky meter, etc.). In this paper, we consider advanced E-boxes with onboard intelligence, which receive signals from the grid operator and are able to reduce home demand or increase power production as in the New Energy and industrial technology Development Organization (NEDO) project of Ohta City [6].

Considerable research activity is focused on the integration of large amounts of distributed energy resources (DERs) in the electrical system. The attention is now oriented toward the use of DERs for improving grid operation by contributing to ancillary services, increasing the energy reserve, and reducing CO_2 emissions. In practice, new facilities are expected to reduce congestion, minimize the production cost, and maintain the frequency and voltage.

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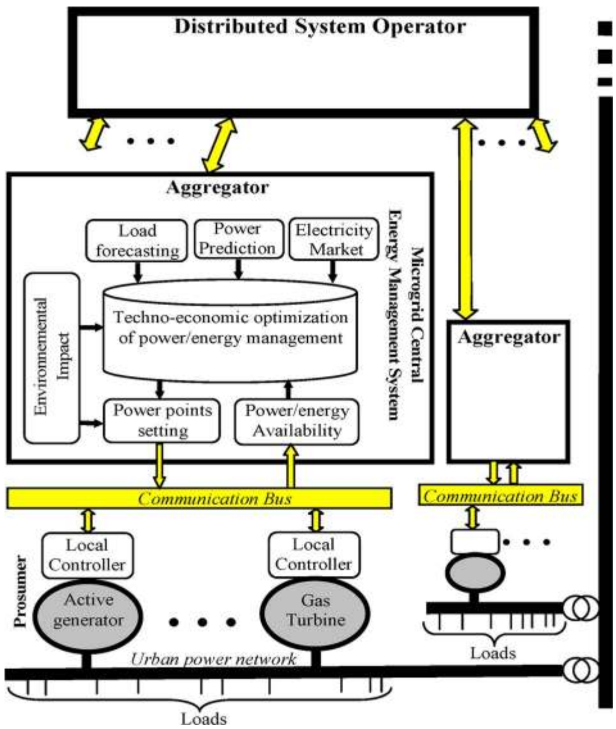


Fig. 2. Framework of the central EMS.

These developments require a fundamental redesign of the grid control. Here, an aggregated architecture of an urban power system is considered as a mean to facilitate the integration of multiple distributed prosumers both in the electrical system and in the market. In this architecture, the aggregators are the key mediators between prosumers and consumers on one side and the markets and the Distributed System Operator (DSO) on the other side (see Fig. 2). The aggregators collect from the DSO (and the markets in future) the requests and signals for prosumers, which are located in an urban area. They gather the "flexibilities" and the contributions provided by prosumers and consumers to form grid services, and they offer theses services to the different power system participants through various markets [7]. At the prosumers' premises and electrical appliances, distributed generation can be controlled and optimized by the E-box, the interface with the external world.

In this paper, home applications are coordinated with conventional production units by a central energy management system (EMS) to form a microgrid (see Fig. 2).

The global objective consists in matching the total power production to the demand in an optimal way [8], [9]. This concept is pertinent in the framework of smart grids through the combined use of an additional communication network within an intelligent EMS and local controllers [10], [11]. This scheme is a step between current grid requirements and future smart grids.

This paper tackles the problem of the optimal operational planning of smart grids in the presence of prosumers. A coordinated management of energy resources is proposed through a communication network. An E-box exchanges data with the central EMS receiving references.

In Section II, this paper recalls the organization of the embedded local energy management of a prosumer. Section III is focused on the general scheme of the microgrid EMS. Finally,

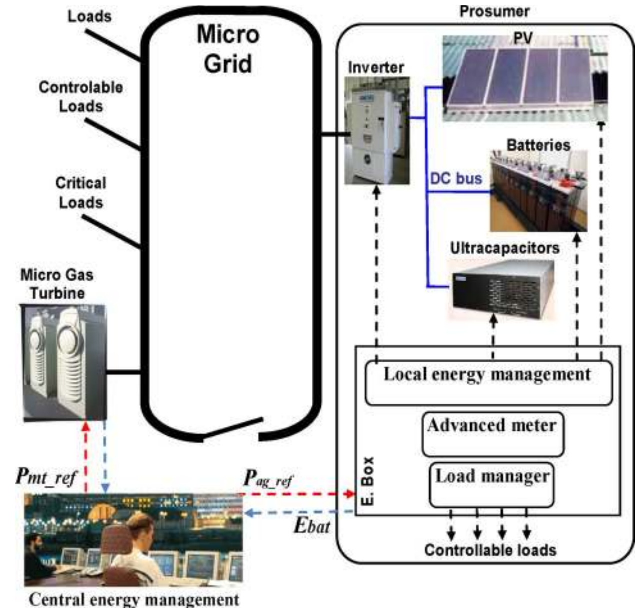


Fig. 3. Microgrid integration of a prosumer and a gas microturbine.

our planning and long-term energy management are detailed in the fourth section. Section V describes the local controller in charge of the coordination of home energy resources whose function is to satisfy grid power references. Experimental results are presented in the last section.

II. Local Energy Management

To facilitate the presentation of theoretical developments, a single prosumer and a gas microturbine are considered in this microgrid (see Fig. 3). The E-box integrates three functions: a load manager, an advanced meter, and a local energy management.

The load manager enables customers to automatically preprogram appliances to turn on when prices are lower or to create energy consumption habits, such as uninterrupted supply of critical loads, time programmable use, etc. Moreover, it can reduce a part of the home power demand when the grid is under stress by disconnecting the offered controllable loads [12]. An advanced meter feeds the local EMS as well as the load manager. Moreover, the utility is able to ping the meter.

Photovoltaic panels are associated with a storage system which includes a set of batteries as a long-term storage device [13], [14] and a set of ultracapacitors as a fast dynamic power regulator [15], [16] (Fig. 1). These are coupled via a dc bus by choppers and are connected to the microgrid by a three-phase inverter [17]. The interesting aspect of this hybrid generator is that it is able to deliver a prescribed power level (P_{ag_ref}) like a conventional generator (for example, a gas microturbine). The local energy management thus allows the use of PV energy according to the grid operator requirement and also at times when the sun is not shining.

In this case, batteries are tapped to provide the required power. To highlight the difference to conventional PV panels, this concept is called an active generator. Excess PV energy is stored in batteries for use when needed, and the local real-time

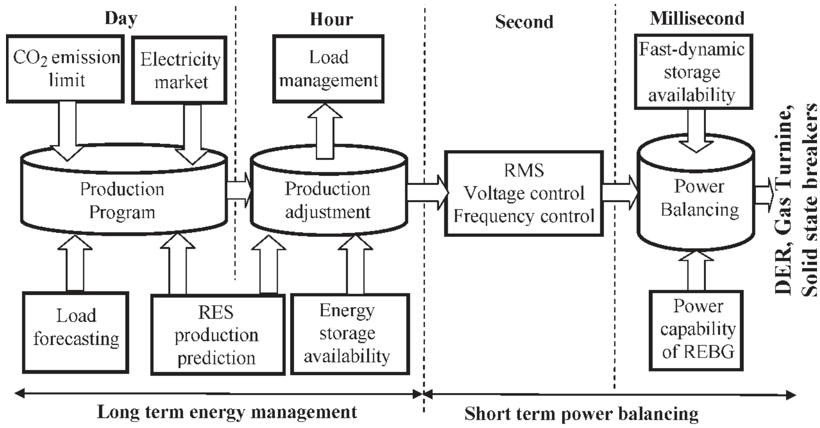


Fig. 4. Timing classification of control functions for EMS.

power control is performed with ultracapacitors. The E-box gives a remote control of the facility to the grid operators to allow faster adjustments to conditions and to give more flexibility to reroute power in a certain offered margin.

III. Microgrid Energy Management

From a general point of view, the task of the central EMS is to manage the power and the energy between sources and loads into the microgrid. The real and reactive power production must then be shared among the DER units (here, a single prosumer) and the gas microturbine. Therefore, the central EMS must assign real and reactive power references and also other appropriate control signals to the renewable energy-based generator (REBG), conventional production units, and controllable loads. Microgrid management is analyzed through various functions that are classified in a timing scale (see Fig. 4).

Long-term energy management includes the following:

1) hourly "Renewable Energy Resource (RES) production forecast," including the time dependence of the prime source, environmental impacts, and cost of generation;
2) management of controllable loads that may be disconnected/shed according to the supervision requirement;
3) provision of an appropriate level of power reserve capacity according to the electricity market and the load demand forecast;
4) maintenance intervals.

Short-term power balancing includes the following:

1) rms voltage regulation and primary frequency control;
2) real-time power dispatching among internal sources of a DER (PV generator, batteries, and ultracapacitors for our example in Fig. 1).

According to the different management objectives, the proposed energy supervision system is implemented in two locations: a central EMS of the whole microgrid for the long-term energy management and a local EMS in the E-box for the short-term power balancing.

A communication between these two management units is set up because the data acquisition and information about the states of each resource (such as the energy capacity and the real-time produced power) are very important for the central EMS of the microgrid.

The control orders from the microgrid central energy management are also sent to the local supervisor (see Fig. 2).

In order to integrate active generators into the electrical system, the central EMS has to be upgraded. Several functions in the central EMS have to be modified or created as the power prediction of the renewable energy, load forecasting, energy storage reserve, peak shaving, maximized use of renewable energy source, reduction of CO_2 emissions, and new power planning (see Fig. 4). In the next section, a long-term energy management is proposed. In the presented case study, the dispatching of reactive power references is not discussed because it is not the scope of this paper. Reactive power references are assumed to be set to a null value.

IV. Long-Term Energy Management

A. PV Power Prediction and Load Forecasting

In the case study, the naturally poor predictability of the level of solar energy is a weakness for the purpose of its use in an electric system. Photovoltaic panels provide electrical power only during the day with a power peak around the midday. Meanwhile, huge production variations may occur.

According to the weather forecasting and the historic database of PV power, a 24-h-ahead approximated PV power prediction profile ($\widetilde{P}_{PV\_24\,\mathrm{h}}$) can be obtained each half hour (see Fig. 5). The load forecasting is also very important for the energy management. Based on historic electrical power production demands, the behavior of the loads can be forecast and estimated. Several factors influence the load in the electrical network: the weather situation (temperature, cloud coverage, etc.), economic activity (huge modifications of load forecasting are necessary during the holiday periods), standard working hours, etc. "Classic" methods of load forecasting are based on meteorological information and historic consumption data [18]. A 24-h-ahead load forecasting profile ($\widetilde{P}_{Load\_24\,\mathrm{h}}$) is given in Fig. 6 with data recorded each half hour.

B. Energy Estimation

For the energy estimation, the initial time point is considered as the start of the day (t_0), and the day's duration is named (Δt). Both parameters depend on the season and the weather conditions.

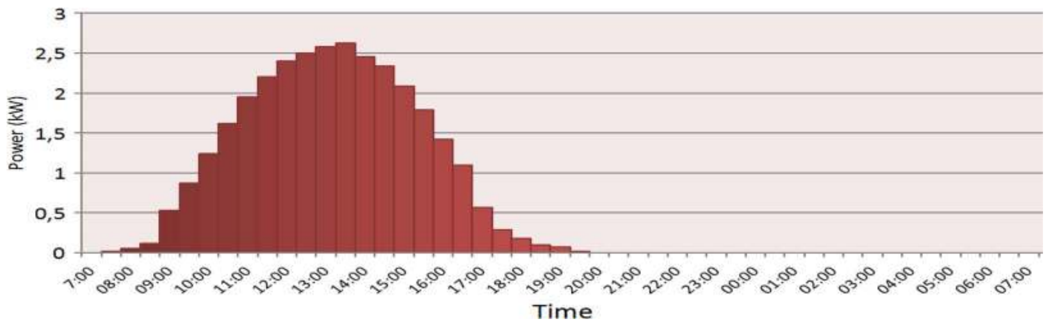


Fig. 5. 24-h-ahead PV power prediction ($\widetilde{P}_{PV\_24\,\mathrm{h}}$).

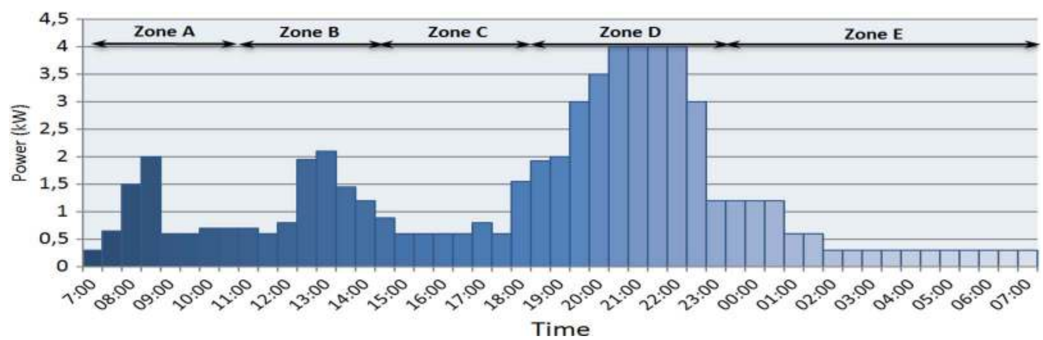


Fig. 6. 24-h-ahead load forecasting ($\widetilde{P}_{Load\_24\,\mathrm{h}}$).

The scheduled energy of the PV production during each 1/2-h interval can be calculated with data from the PV power prediction as

$$\widetilde{E}_{PV\_1/2\,\mathrm{h}} = \int_{t_0+nTe}^{t_0+(n+1)Te} \widetilde{P}_{PV\_24\,\mathrm{h}}(t)dt = Te.\widetilde{P}_{PV\_24\,\mathrm{h}}(t_0+n.Te) \quad \text{with } Te = 30 \text{ min and } n \in \{0,1,\ldots,47\}. \tag{1}$$

In order to plan the production program, the energy, which is demanded by the load, is also estimated during the same interval

$$\widetilde{E}_{Load\_1/2\,\mathrm{h}} = \int_{t_0+nTe}^{t_0+(n+1)Te} \widetilde{P}_{Load\_24\,\mathrm{h}}(t)dt = Te.\widetilde{P}_{Load\_24\,\mathrm{h}}(t_0+n.Te). \tag{2}$$

The rated power of the gas microturbine ($P_{MGT\_\max}$) is 33 kW. In order to minimize the energy losses and air pollution at each start of the gas turbine, the gas turbine should always work. Therefore, in the case of low power demand, the turbine is forced to work with a low power level ($P_{MGT\_\min} = (1/2)P_{MGT\_\max}$), corresponding to the minimum energy

$$\widetilde{E}_{MGT\_1/2\,\mathrm{h}\_\min} = \int_0^{Te} P_{MGT\_\min}dt = Te.P_{MGT\_\min}. \tag{3}$$

As the system is connected to the grid, the gas microturbine could be switched off for maintenance. In this case, the missing power will be provided by other producers in other urban power networks through the distribution network.

Because of the rated power of the batteries ($P_{bat\_\max}$), the exchanged energy during 1/2 h with the batteries is limited as

$$\widetilde{E}_{bat\_1/2\,\mathrm{h}\_\max} = \int_0^{Te} P_{bat\_\max}dt = Te.P_{bat\_\max}. \tag{4}$$

C. Determinist Half-Hour Operational Planning

In this studied case, two power sources are considered: a PV-based active generator (at the prosumer home) and a gas microturbine. Because of the renewable energy benefits (less gas emission and low operating cost), the PV-based active generator is considered as the prior source, and the gas microturbine is considered as a backup source for the missing energy. The objective is to set one charging/discharging cycle for batteries every day. The depth of the discharge is maintained between 0% and 70% during normal operation to increase the battery lifetime. Here, the storage battery capacity is 10 kWh. Moreover, the rated battery power ($P_{bat\_\max}$) is also considered.

According to daily predictions of the available power and energy from the PV ($\widetilde{P}_{PV\_24\,\mathrm{h}}, \widetilde{E}_{PV\_1/2\,\mathrm{h}}$) and the required power and energy of the loads ($\widetilde{P}_{Load\_24\,\mathrm{h}}, \widetilde{E}_{Load\_1/2\,\mathrm{h}}$), a power production planning for the prosumer (P_{AG_ref0}) and for the microturbine (P_{MGT_ref0}) must be determined. The central EMS refreshes the power references each 30 min. As no power is available from PV panels during the night, power references are calculated separately for the night and for the day.

In the day ($t_0 < t < t_0 + \Delta t$) and for each 1/2-h period, two cases are considered.

Case 1: If the available PV energy added with the minimum gas turbine energy is less than the demanded load energy $(\widetilde{E}_{PV\_1/2\,\mathrm{h}} + \widetilde{E}_{MGT\_1/2\,\mathrm{h}\_min} < \widetilde{E}_{load\_1/2\,\mathrm{h}})$, the PV panels can work with a maximum power point tracking (MPPT) algorithm, and all PV power is injected in the grid. The gas microturbine has to generate the missing power

$$P_{AG\_ref0} = \widetilde{P}_{PV\_24\,\mathrm{h}} \tag{5}$$

$$P_{MGT\_ref0} = \widetilde{P}_{Load\_24\,\mathrm{h}} - P_{AG\_ref0}. \tag{6}$$

Case 2: Otherwise, the available PV energy added to the minimum gas turbine energy is more than the demanded load energy. Priority is then given to the renewable energy for the electrical production so that the gas microturbine works with minimum power and the active generator power is limited to the missing power

$$P_{AG\_ref0} = \widetilde{P}_{Load\_24\,\mathrm{h}} - P_{MGT\_\min} \tag{7}$$

$$P_{MGT\_ref0} = P_{MGT\_\min}. \tag{8}$$

The excess PV energy will be managed by the local controller (paragraph V).

The energy management during the night ($t_0 + \Delta t < t < t_0 + 24$ h) depends on the available energy from batteries in homes. This energy can be estimated or communicated by the E-box to the central EMS. In the night, two cases are also distinguished. For both cases, the batteries have to be discharged in order to be ready for charging the next day at t_0. According to the stored energy $(\widetilde{E}_{bat}(t_0 + nTe))$ and the rated energy $(\widetilde{E}_{bat\_1/2\,\mathrm{h}\_\max})$, the available energy of the batteries during the next 1/2 h is obtained

$$\widetilde{E}_{bat\_1/2\,\mathrm{h}\_rest}(t) = \min\left[\widetilde{E}_{bat\_1/2\,\mathrm{h}\_\max}, \widetilde{E}_{bat}(t_0 + nTe)\right]. \tag{9}$$

The aforementioned two cases for the night operation are as follows.

Case 1: If the available stored battery energy added to the minimum gas turbine energy is more than the demanded energy from the loads $(\widetilde{E}_{bat\_1/2\,\mathrm{h}\_rest} + \widetilde{E}_{MGT\_1/2\_min} > \widetilde{E}_{load\_1/2\,\mathrm{h}})$, priority is given to the active generator for the electrical production since it has enough previously stored energy from PV panels. The gas turbine will work with minimum power

$$P_{AG\_ref0} = \widetilde{P}_{Load\_24\,\mathrm{h}} - P_{MGT\_\min} \tag{10}$$

$$P_{MGT\_ref0} = P_{MGT\_\min}. \tag{11}$$

Case 2: Otherwise, the stored battery energy added with the minimum gas turbine energy is less than the demanded energy from the loads. Then, the power reference of the active generator is calculated in order to discharge the batteries, and the gas turbine must generate the missing power

$$P_{AG\_ref0} = \frac{\widetilde{E}_{bat\_1/2\,\mathrm{h}\_rest}}{Te} \tag{12}$$

$$P_{MGT\_ref0} = \widetilde{P}_{Load\_24\,\mathrm{h}} - P_{AG\_ref0}. \tag{13}$$

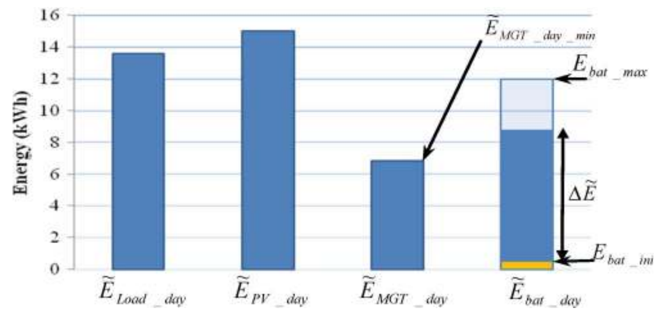


Fig. 7. Energy analysis for the day.

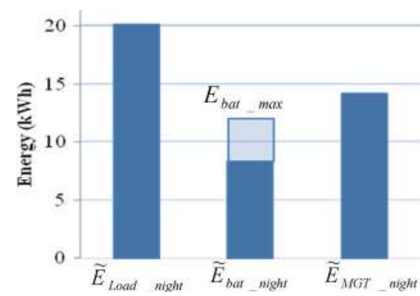


Fig. 8. Energy analysis for the night.

D. Implementation and Obtained Results

In order to illustrate the theoretical results, the power planning (24 h ahead) of the load forecasting (see Fig. 6) is considered, as well as the estimated PV power (see Fig. 5) with $t_0 = 7\mathrm{h}00$ and $\Delta t = 12\mathrm{h}30$. Estimations of the required energy for the loads $(\widetilde{E}_{Load\_day})$ and the available energy from the PV panels $(\widetilde{E}_{PV\_day})$ during the day ($t_0 < t < t_0 + \Delta t$) show that too much renewable energy is available (see Fig. 7).

As the gas microturbine must produce the minimum energy during the day, the surplus energy is estimated as

$$\Delta\widetilde{E} = \widetilde{E}_{PV\_day} - \widetilde{E}_{Load\_day} + \widetilde{E}_{MGT\_day\_\min} < E_{bat\_\max} \tag{14}$$

$$\widetilde{E}_{MGT\_day\_\min} = \int_{t_0}^{t_0+24\,\mathrm{h}} P_{MGT\_\min} dt. \tag{15}$$

This energy can be stored in batteries. The required energy from the gas microturbine for night operation is then deduced (see Fig. 8)

$$\widetilde{E}_{MGT\_night} = \widetilde{E}_{Load\_night} - \widetilde{E}_{bat\_night} \tag{16}$$

with $\widetilde{E}_{bat\_night} = \Delta\widetilde{E}$.

As a communication network exists, it is easy to replace the estimated value of the battery energy with a sensed value, which

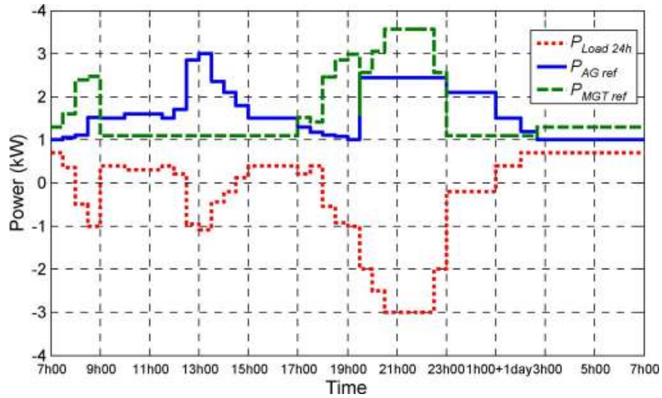


Fig. 9. Power references from the power planning in the central energy management.

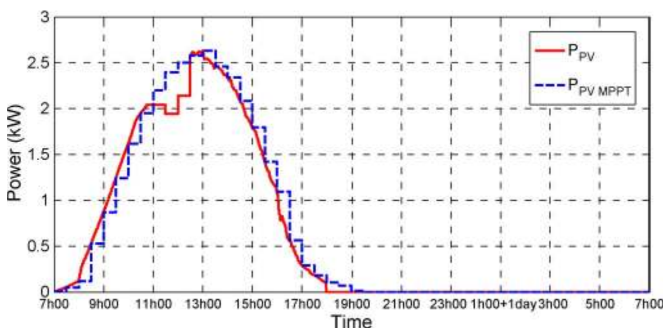


Fig. 10. Measured PV power and the estimated PV power.

is sent by the E-box at the beginning of the night $(t_0 + \Delta t)$. Between 7h00 and 9h00, the PV power is not enough (see Fig. 5); the power reference is well calculated for the gas microturbine (see Fig. 9).

After 9h00, the turbine power reference is set to the minimum value until 17h00. At 19h30, the power reference for the prosumer is adapted to discharge the batteries; the peak value of the turbine power reference is reduced (see Fig. 9). Fig. 10 shows the sensed value of the PV power and the theoretical one, which can be generated with an MPPT algorithm. Between 11h00 and 12h30, the available PV power exceeds the requested power from the loads. Fig. 10 shows that all the PV power is not delivered to the grid. The local EMS has stored or limited part of the available PV power; the implementation is detailed in the next section.

Fig. 11 shows that the real sensed value of the total load power may be significantly different from the 24-h-ahead estimated one. The task of the primary control is to eliminate these errors. This primary control is included inside each local energy management of generators.

V. Local Controller of the PV Active Generator

A. Local Energy Management

The central EMS sends a requested power reference P_{AG_ref0} to the active generator each half of an hour. The local controller has to distribute this power reference inside the PV active generator.

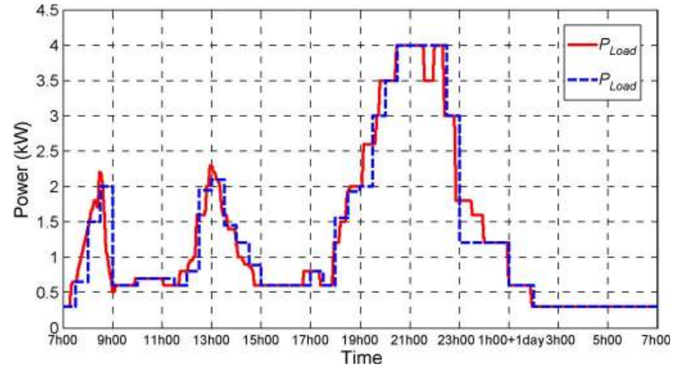


Fig. 11. Measured load and the estimated load.

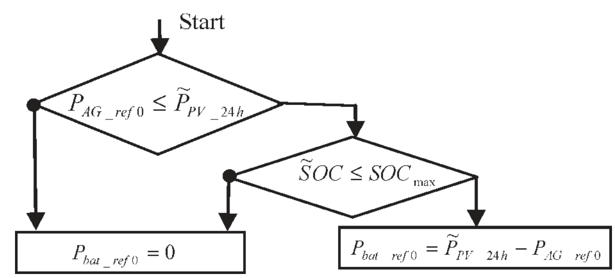


Fig. 12. Flow diagram of the battery charging for the battery management.

In the active generator of the prosumer, two different types of energy storage technologies are coupled with the PV generator. Lead acid batteries are chosen because of their low cost and their wide availability. They can be used as long-term energy storage in the case of PV overproduction. In the case of PV energy shortage, they will be used to provide power. However, PV panels are not an ideal source for battery charging as the output is unreliable and is dependent on weather conditions. It can cause deep discharging, undercharging, and overcharging of batteries. They may damage batteries and shorten their lifetime [19], [20]. Therefore, in order to optimize the battery use, a single charging/discharging cycle is set during the day. Moreover, during every half of an hour, the battery charging power reference (P_{bat_ref0}) is constant.

The charging of batteries is decided if the available PV power in the MPPT $(\widetilde{P}_{PV\_24\,h})$ is higher than the requested power reference (P_{AG_ref0}) and if batteries are not full (see Fig. 12). The state of charge $(\widetilde{SOC})$ has to be estimated [21], [19] and compared with the maximum value $(\widetilde{SOC}_{\max})$.

The night case is simpler as the PV power is null. The batteries are considered as the main source until the minimum value of the batteries $\widetilde{SOC}$ is achieved.

For security reasons, the obtained battery power reference is limited to the rated power value $(P_{bat\_\max})$.

B. Primary Frequency Regulation

The central EMS sends a wished power reference P_{AG_ref0} to the active generator each half of an hour. This quantity is the planned exchanged power of the active generator in a long time range. As uncertainties exist not only in the load forecasting but also in the PV power prediction, a primary frequency control must be used to adjust the power production

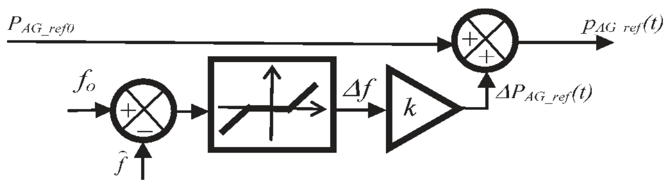


Fig. 13. Droop controller for primary frequency control.

of generators in real time in order to achieve the real-time power balancing. A primary frequency control has been implemented onto the active generator in order to ensure the short-term power balancing (see Fig. 13).

The grid frequency control is a conventional solution to the real-time power balancing [22], [23]. When the frequency deviation exceeds a predefined threshold value, the controller is activated to increase or decrease the power for restoring the power balance. The primary frequency control contribution of the generator is based on a droop constant, which gives the additional power that is supplied as a function of the frequency deviation [24]–[26] (see Fig. 13)

$$\Delta P_{AG\_ref}(t) = -k\Delta f(t) = -k\left(f_0 - \hat{f}(t)\right). \tag{17}$$

f_0 is the frequency in the normal operation (50 Hz for our case study), and $\hat{f}$ is the sensed value of the frequency. The power/frequency constant is calculated as

$$k = \frac{1}{s}\frac{P_{AG\_rated}}{f_0} \tag{18}$$

with the droop $s = 5\%$ and P_{AG_rated} being the maximum available power, which can be exported to the microgrid.

C. Real-Time Power Balancing Inside the Active Generator

The active generator has to provide the real-time power reference $(p_{AG\_ref}(t))$, which is the sum of the secondary power reference (P_{AG_ref0}) with the primary power reference $(\Delta P_{AG\_ref}(t))$.

In the active generator of the prosumer, batteries are used to provide the guaranteed energy to the microgrid operator. The real-time power balancing must be implemented by a power buffer with fast dynamic capabilities. Ultracapacitors are fast dynamic storage systems with high power exchange capabilities. They are suitable for the optimal charging of the battery and for supplying peak power to the grid if necessary, but their energy density is low.

The real-time power balancing depends on the availability of the ultracapacitors. They can be checked if the sensed value of the ultracapacitor voltage $(\hat{u}_{uc})$ is in the security domain, i.e., between a minimum value $(u_{uc\_\min})$ and a maximum value $(u_{uc\_\max})$ (see Fig. 14). In this "storage mode," ultracapacitors can be used to increase or decrease the exchanged power with the grid in order to represent a faithful real-time power reference $(p_{AG\_ref}(t))$.

If ultracapacitors are overloaded $(\hat{u}_{uc} > u_{uc\_\max})$, excess PV power cannot be stored in them, so the produced PV power must be limited to satisfy the real-time power reference. This mode is called the "PV limitation mode."

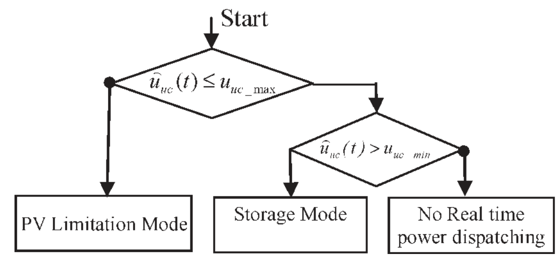


Fig. 14. Selection of operating modes.

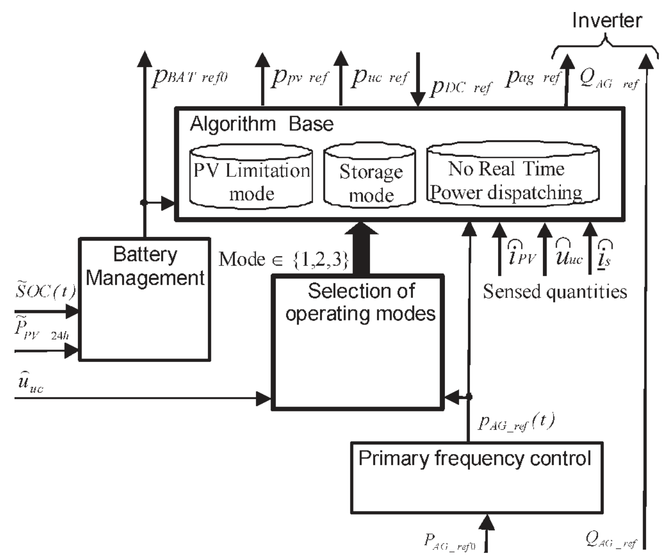


Fig. 15. Organization of the power control of the local controller.

If the PV power is insufficient and ultracapacitors are discharged, it is not possible to supply the real-time power reference. This mode is called the "no real-time power dispatching mode."

Thus, one algorithm (corresponding to one operating mode) is executed and calculates the power references for each source according to the selected operating mode and the measured quantities (see Fig. 15). These power references are then transformed to current or voltage references for closed loop controls [27].

D. Real-Time Power Dispatching

The real-time power dispatching among the batteries, the ultracapacitors, and the PV generator must be set in order to deduce the prescribed power references.

Mode No 1 (Storage Mode): For this mode, the produced electric power from PV panels may be higher or lower than the power reference $(p_{AG\_ref}(t))$. Moreover, ultracapacitors are available and can be used to compensate for this difference. Therefore, the active generator can deliver the electric power to meet the grid power references.

During the day, the photovoltaic panels are working in MPPT with a particular algorithm (f_{MPPT}), which requires the sensed value of the PV current $\hat{i}_{pv}$

$$p_{pv\_ref} = f_{MPPT}(\hat{i}_{pv}). \tag{19}$$

For the theoretical analysis, batteries and ultracapacitors are assumed to be in generating mode. The power flow from the

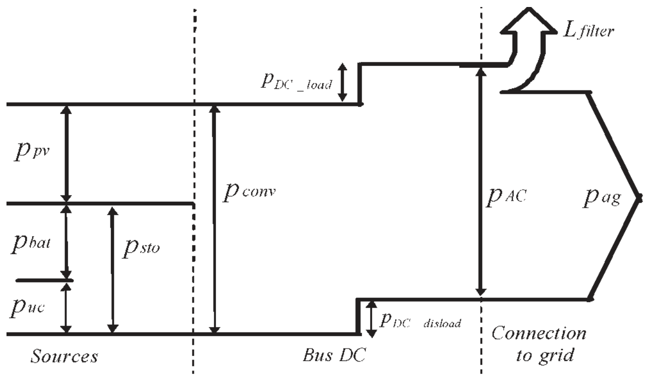


Fig. 16. Power flow in the storage mode.

TABLE I
MODELING AND CONTROL EQUATIONS OF THE POWER

Modeling equations		Power management	
$p_{sto} = p_{bat} + p_{uc}$	(R1)	$p_{uc\_ref} = p_{sto\_ref} - \widehat{p}_{bat}$	(R1c)
$p_{conv} = p_{pv} + p_{sto}$	(R2)	$p_{sto\_ref} = p_{conv\_ref} - \widetilde{p}_{pv}$	(R2c)
$p_{AC} = p_{conv} - p_{DC}$	(R3)	$p_{conv\_ref} = p_{AC\_ref} + p_{DC\_ref}$	(R3c)
$p_{ag} = p_{AC} - L_{filter}$	(R4)	$p_{AC\_ref} = p_{ag\_ref} + \widetilde{L}_{filter}$	(R4c)

sources to the grid is described in Fig. 16. The total exchanged power with both storage units is called p_{sto}. The exchanged power with the capacitor of the dc bus is called p_{dc}. In Fig. 16, this power is composed of a positive part (p_{dc_load} to increase the dc voltage if necessary) and a negative part ($p_{dc\_disload}$ to decrease the dc voltage if necessary). The modeling equations of the power flow are summarized in Table I.

If the resistor of the grid filter (R) is known, losses can be estimated with the sensed grid currents $(\widehat{i}_s)$

$$\widetilde{L}_{\text{filter}} = 3 \cdot R \cdot \widehat{i}_s^2. \quad (20)$$

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 I) [28]. Part of this power is required to regulate the dc bus (p_{dc_ref}). This power reference is taken into account in the power flow management (*R3c* in Table I). The reference of the exchanged power with both storage units is calculated by using an estimation of the produced PV power (*R2c*). Then, the power reference for ultracapacitors is obtained by taking into account the sensed value of the batteries' power $(\widehat{p}_{bat})$ in the control equation (*R1c*).

Mode No 2 (Limitation Mode): In this mode, ultracapacitors cannot be used to manage the real-time power dispatching because they are fully charged. If the available power from the PV panels (in MPPT, $\widetilde{P}_{PV\_MPPT}$) is more than the required power reference, it is not possible to send all PV power into storage units. Hence, ultracapacitors have to be set up in standby mode

$$p_{uc\_ref}(t) = 0. \quad (21)$$

The produced power from the PV panels must be limited to the power reference set point

$$p_{pv\_ref}(t) = p_{conv\_ref}(t) - p_{bat\_ref}(t). \quad (22)$$

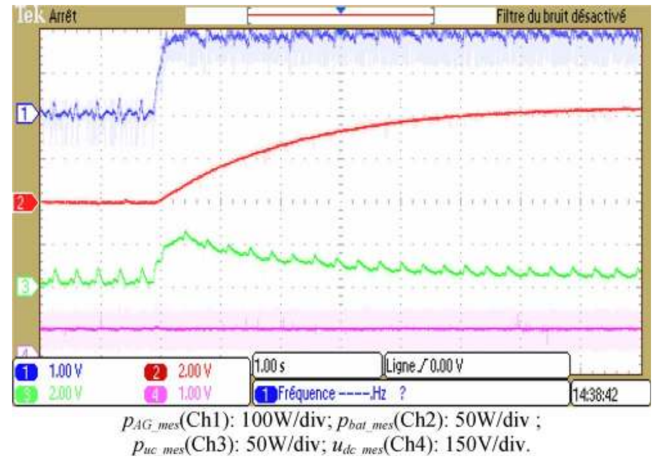


Fig. 17. Experimental results in the night mode.

The PV converter controller can reduce the PV power production by regulating the voltage across the PV panels (u_{PV}).

Mode No 3 (No Real-Time Power Dispatching Mode): In this mode, ultracapacitors are disloaded and so cannot be discharged anymore. They cannot be used to give more power if the PV power is not enough for the power supply. The inner power balancing is performed by the ultracapacitors. Their state of charge must be checked, and typically, their voltage must remain over 5% of their nominal value for a normal operation in modes No 1 and No 2. Otherwise, it is not possible to control the output grid power, and then, it is set as

$$p_{ag\_ref}(t) = 0. \quad (23)$$

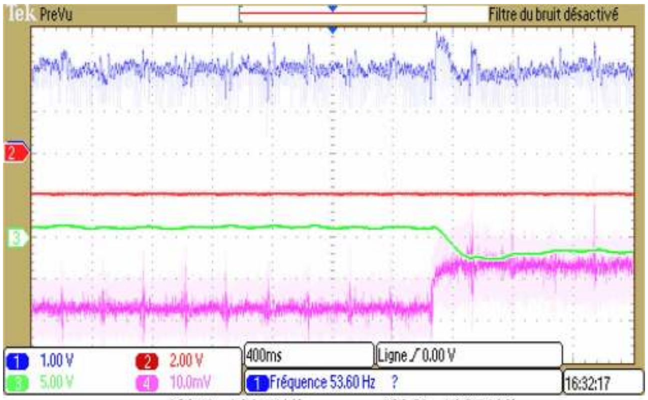
As no power is sent to the grid, the PV power loads the supercapacitors, and the PV panels must work in MPPT.

VI. EXPERIMENTAL RESULTS OF A CASE STUDY

In order to test our energy management, a prototype of the studied active generator has been built. A set of 10-kWh batteries and two 112-kW (peak power) ultracapacitor modules are used as storage components. Experimental results are presented when the hybrid generator is operated in the storage mode and uses ultracapacitors.

In the night mode, there is no electrical production from PV power. Fig. 17 shows the variation of the grid power and the powers from both storage units when a step change of the grid power reference (P_{AG_ref0}) from 0 to 200 W occurs. The batteries are ordered to be discharged. However, their power increases slowly and cannot instantaneously satisfy a sudden power change. Experimental results show that the ultracapacitors are discharged with a high power in order to meet this power reference.

The second experimental test presented corresponds to daytime operation. A constant 200-W power reference (P_{AG_ref0}) is received. The batteries are charged with a 100-W power reference. In the presented experimental results, the PV power production varies from 300 to 450 W (see Fig. 18). When the PV production increases quickly, the ultracapacitors help to perform the power balancing while charging more power with a higher current. The sensed batteries' power remains constant, and variations of the generated grid power are smaller.



p_{AG_mes}(Ch1): 100W/div; p_{bat_mes}(Ch2): 100W/div ; p_{uc_mes}(Ch3): 150W/div; p_{PV_mes} (Ch4): 150W/div.

Fig. 18. Experimental results in the day mode.

VII. Conclusion

In this paper, a microgrid organization has been studied in order to define the roles and the required control systems for the integration of dispersed PV generators and DER units in the electrical system. The main problem is that the output power from most REBGs fluctuates depending on weather conditions when the power quality of the grid may decrease. Experiences currently show that the maximum penetration ratio of these passive PV generators in European island networks is 30%. One way to increase the penetration ratio is to upgrade actual PV generators in order to transform them into controllable generators. These active generators are new flexibilities for the grid system operator. In this paper, a solution has been proposed to promote and coordinate large dispersed small PV-based generators and a gas microturbine in the plan to lower energy costs for customers, achieve energy independence, and reduce greenhouse gas emissions. This work falls into the framework of smart grids since the solution relies on an enhanced EMS and a communication network. Cases with complex systems, including more active PV-based generators and gas turbines, are subject to future works.

A determinist operational power planning has been proposed to perform the day-ahead power scheduling for the conventional and PV generators. The presented scheme relies on PV power predictions and load forecasting. The scheme also sets out plans for the use of the distributed battery storage. Power references are communicated to customers. An open local controller inside an E-box has been developed and presented in order to satisfy grid operator requirements according the local state of the sources (state of the batteries' charge, solar radiation, etc.). At the customer side, two storage technologies are used to enable grid demand management and renewable energy integration. Batteries are used to ensure an energy reserve for the grid operator. Supercapacitors are used to balance fast power variations coming from the PV generator and from the primary frequency control. A strategy has been presented to drive them according to the solar energy resources and grid requirements. Experimental results of the proposed smart grid solution for planning and operating the microgrid are presented. Currently, further research is aimed at hypothetical business cases associated with smart grids and distributed resource integration to provide more value to the microgrid management.

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