Provision of Ancillary Services by a Smart Microgrid: An OPF Approach

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***Abstract*—Ancillary services are all services required by the transmission (TSO) or distribution system operator (DSO) to maintain the integrity and stability of the transmission or distribution system as well as the power quality. Ancillary services that can be provided by a microgrid in grid-connected operation are frequency control support, voltage control support, congestion management, reduction of grid losses, and improvement of power quality.**

This paper presents the optimization problems used in the 3DMicroGrid project to determine the set-points of the different resources present in the microgrid to provide ancillary services to the power system in grid-connected operation: frequency control, voltage control and load curtailment.

Results of the optimization of the pilot microgrid used in 3DMicroGrid are presented.

I. Introduction

According to the European projects *Microgrids* and *More microgrids* [1], a microgrid is defined as follows: *"Microgrids comprise LV distribution systems with distributed energy resources together with storage devices and flexible loads. Such systems can be operated in a non-autonomous way if interconnected to the grid, or in an independent way if disconnected from the main grid. The operation of microsources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently"*.

Typically, a microgrid is limited to several MW of peak demand, although on a larger scale, it is easier to incorporate resources to improve controllability to reduce the intermittent nature of renewable generation and consumption [2].

Besides, Ancillary Services are all services required by the transmission (TSO) or distribution system operator (DSO) to maintain the integrity and stability of the transmission or distribution system as well as the power quality. Services include both mandatory services and services subject to competition [3], [4]. Ancillary services that can be provided by a microgrid in grid-connected operation are frequency control support, voltage control support, congestion management, reduction of grid losses, and improvement of power quality.

The ERANETMED 3DMicroGrid project [5] focus on the design, development and demonstration of a future-proof active smart micro-grid system to integrate and optimize multiple small to medium sized energy sources and loads, using the campus of the Malta College of Arts, Science and Technology (MCAST) as pilot project Micro-Grid. Innovative methods are being used for enhancing the accuracy of the available resources by incorporating parameters estimation method in combination with the measurements from the real field. The proposed techniques will be generalized in order to be applicable in any micro-grid scale and any micro-grid components.

This paper presents the optimization problems used in the 3DMicroGrid project to determine the set-points of the different resources present in the microgrid to provide ancillary services to the power system in grid-connected operation: frequency control, voltage control and load curtailment.

The remainder of the paper is organized as follows. The next section provides an introduction to the microgrid operation and control issues, focusing in the provision of ancillary services to the DSO. Section III describes the proposed OPF formulation to determine the optimal scheduling of the microgrid resources, taking into account the constraints imposed by the provision of ancillary services. Section IV describes the MCAST microgrid used to test the proposed OPF problems, and Section V presents some numerical results, focusing on the cost associated to the provision of the required ancillary services. Finally, Section VI presents the conclusions of the studies performed.

II. Microgrid Operation and Control

A. Microgrid Control

Control is a fundamental issue in microgrids, so that they appear to the upstream DSO as a coordinated unit. Such control can be implemented in a variety of ways, ranging from centralized control to fully decentralized control, depending on the degree of responsibility assumed centrally or locally by the different resources.

Although there is no generalizable structure to any microgrid, depending largely on the type of microgrid and its existing infrastructure, it is common for the microgrid control to be organized in a hierarchical structure at three levels [6]:

- A primary, local level, composed of several microsource controllers (MCs) which are responsible for controlling distributed energy resources.

- A secondary, centralized level, consisting of the Microgrid Central Controller (MGCC) responsible for the coordination and monitoring of the various local MCs.
- A centralized, tertiary level, in charge of providing the main interface between the MGCC and external actors such as DSO. The tertiary level is equipped with scheduling routines that provide optimal setpoints for the MCs, based on the overall optimization objectives [7].

The hierarchical structure of the microgrid can be operated in a centralized or decentralized way. In centralized control, secondary and tertiary levels are responsible for the optimization of the operation, based on electricity prices and fuel costs, and taking into account grid security concerns and possible ancillary services requests by external agents.

Centralized control is more appropriate when the resources of the microgrid have common objectives or a common operational structure (e.g., the MCAST campus microgrid) [8].

B. Participation in Electricity Markets

Due to their relatively small size regarding peak power, microgrids generally do not participate in energy markets and channel their participation through aggregators or an Energy Service Company (ESCO). Alternatively, in some countries, the direct management of microgrids by the TSO, in the case of large microgrids, or a DSO for smaller microgrids, is also a possible model.

Concerning microgrid demand management, the following alternatives can be considered [9]:

- Price-based demand response implementations respond to time-based changes in the prices of the energy, so it is necessary to know in advance the energy prices, either as a result of a short-term electricity market or based on the hourly rates established in advance.
- Incentive-based demand response programs facilitated by utilities, retail companies or DSOs to introduce load reduction incentives. Load reductions are coordinated by an operator and can include direct load control.

C. Provision of Ancillary Services

The provision of ancillary services in grid-connected mode is usually managed through long-term contracts with TSO (frequency control support) or DSO (voltage control support and congestion management), which may include real-time service requirements (voltage & reactive power support; congestion management through load curtailment).

The frequency control of a power system is implemented by a central controller, the Load-Frequency Control in Europe or Automatic Generation Control in the USA, based on a slow Proportional-Integral (PI) controller that restores the frequency of the grid when the error is over a specific value (e.g., 50 mHz) [10].

As for the local primary control in islanded mode, the dispatchable generation units of the microgrid must implement a P/f droop control locally, thus allowing the microgrid to provide frequency control to the system in grid-connected operation. Besides, the low inertia typical of isolated microgrids results in larger frequency deviations after an event, and virtual synchronous generators (eg, battery energy storage devices, BES) can be required to emulate rotating inertia and provide primary frequency response [11].

Voltage control can be implemented by using a similar approach as the frequency control. When the voltage is outside a specific range, a slow PI control compensates the voltage error in the microgrid by sending orders to MCs to regulate their reactive power support. This control may include specific constraints associated with maintaining a certain reactive power demand in the Point of Common Coupling (PCC) of the microgrid.

In consequence, voltage control can be provided by the microgrid to the DSO, under long-term agreements (eg, limits on the power factor of the microgrid in the PCC) or under demand (eg, request to reduce reactive power consumption or to maintain a desired voltage), in a similar way than load curtailment or peak shaving provision to the DSO.

D. Uncertainty Management in Microgrids

Traditionally, the short-term scheduling of generation resources in power systems haven been performed in two stages. In the first stage, units are “committed” to meet the expected load during each hour, based on generators start-up and shut-down costs, operating costs and ramp constraints (Unit Commitment). A Stochastic Unit Commitment muy be used to deal with the uncertainties of the problem [13]. In the second stage, after most uncertain inputs have been realized (ie, minutes to hours ahead of the time of implementation), the power outputs of committed units are decided to meet the load (Economic Dispatch). This two-stage decision process is used to manage the uncertainties involved and the constraints associated to generation resources.

For microgrids operation scheduling, a similar two-stage scheduling procedure is used, starting with a day-ahead Unit Commitment of the microgrid resources, and followed by a short-term Economic Dispatch of resources [14], [15]. Stochastic programming is normally used in the day-ahead Unit Commitment to deal with the uncertainties of the problem, and a deterministic optimization problem is used for the Economic Dispatch, which is sequentially solved with the best forecast available for the uncertain parameters (eg, loads and solar/wind generations). Note that both problems must satisfy the physical constraints of the available resources (generators, BES devices) and the grid (electrical constraints), as well as the constraints imposed by the ancillary services contracted or that can be required in real time [16].

III. Optimization Problems

A. Sets and indexes

- Scheduling period in hours, $t \in \mathcal{H}$
- Set of thermal generators, $g \in \mathcal{G}$
- Set of photovoltaic generation devices, $pv \in \mathcal{S}$
- Set of essential, non-interruptible loads, $ni \in \mathcal{E}$
- Set of non-essential, interruptible loads, $id \in \mathcal{I}$
- Set of BES devices, $bs \in \mathcal{B}$

- Set of electrical buses in the network, $i \in \mathcal{N}$

B. Uncertain parameters

- Price scenarios: $p \in \Omega_p$ with probability μ_p, leading to expected hourly prices $\pi_t^p, \forall t \in \mathcal{H}$.
- Photovoltaic generation (PV) scenarios in pu: $s \in \Omega_s$ with probability μ_s, leading to expected hourly PV generations $p_{pv,t}^s, \forall t \in \mathcal{H}, \forall pv \in \mathcal{S}$.
- Load scenarios: $d \in \Omega_d$ with probability μ_d, leading to expected hourly demands $p_{ni,t}^d$ and $p_{id,t}^d$, for each non-essential demand (interruptible or candidate to load shedding), $id \in \mathcal{I}$, and essential demand, $ni \in \mathcal{E}$, $p_{id,t}^d$, $p_{ni,t}^d, \forall t \in \mathcal{H}$. Reactive power demands are also forecasted, $q_{id,t}^d$, $q_{ni,t}^d, \forall t \in \mathcal{H}$.

C. Stochastic Optimal Power Flow (SOPF)

The complete Stochastic OPF formulation is presented in Table I and commented below.

1) Objective function: Sum over all expected scenarios of the energy cost (consumed energy from the grid), cost of internal generation (diesel generators), and cost of load shedding, if required, equation (1), with $mp_t^{s,d}$ being the hourly demand of the microgrid, $C_{g,t}^{s,d}(p_{g,t}^{s,d})$ is the cost of generator g in the hour t, and $C_{id,t}^{s,d}$ is the cost associated to the interruptible load id that has been shed in hour t, in the different PV and demand scenarios.

2) Constraints:

- Network equations for each node i, characterized by the complex voltage $V_i^{s,d} \angle \varphi_i^{s,d}$, in demand and PV scenarios d and s, and with G_{ij} and B_{ij} the real and imaginary components of the admittance matrix, equations (2) and (3), where g, pv and bs are respectively generation, PV and battery storage resources, and loads are separated between non-interruptible, ni, and interruptible loads, id. Note that $x \subset i$ indicates location of the corresponding device x in node i.
  Load shedding requires and additional variable $ls_{id,t}^{s,d}$ ($ls \in [0, 1]$) to take into account the maximum expected demand, equation (4), with $pe_{id,t}^d$ and $qe_{id,t}^d$ the maximum active and reactive expected demand of the load id in hour t and demand scenario d.
- Operational limits on voltages and branch flows, equations (5) and (6), where $s_{ij}^{s,d}$ is the apparent power in branch ij, between nodes i and j, in demand and PV scenarios d and s.
- Limits of generators, equation (7), where $u_{g,t}^{s,d}$ is a binary variable that defines the status on-off of the generator g in the t hour, in demand and PV scenarios d and s.
- Limits and energy stored in BES devices, equations (8) and (9), where $pc_{bs,t}^{s,d}$ and $pd_{bs,t}^{s,d}$ are the active power of the BES in charging and discharging periods, with efficiency η_c and η_d respectively, $q_{bs,t}^{s,d}$ is the reactive power, subject to inverter limits S_{bs}^{max}, and $soc_{bs,t}^{s,d}$ is the *state of charge* of the BES, subject to energy storage limits.

Note that BES devices are required to provide reactive power, but PV devices are not.

The objective of the SOPF is to minimize the expected operating and energy costs of the microgrid, subject to the uncertainty in demand, PV generation, and energy prices. The problem provides operational programs of the different resources, i.e., available generators ($p_{g,t}^{s,d}$ and $q_{g,t}^{s,d}$), storage devices ($pc_{bs,t}^{s,d}$, $pd_{bs,t}^{s,d}$,$q_{bs,t}^{s,d}$ and $soc_{bs,t}^{s,d}$), and load shedding in non-essential loads ($ls_{id,t}^{s,d}$).

Note that a ”robust” scheduling problem can be formulated using unique commitment variables in all demand and PV scenarios (ie, $p_{g,t}$, $pc_{bs,t}$, $pd_{bs,t}$ and $soc_{bs,t}$), except for the load shedding and reactive power variables that are supposed to adapt to each scenario.

D. Constraints Associated to Ancillary Services

We consider the following constraints associated to ancillary services requested by the DSO:

- Reactive demand in the PCC:
  $$mq_t^{s,d} \leq \phi_t \cdot mp_t^{s,d} \qquad \forall t, s \in \Omega_s, d \in \Omega_d \tag{10}$$
  $mp_t^{s,d}$ and $mq_t^{s,d}$ being the active and reactive power demand of the microgrid during the hour t, in the different PV and demand scenarios, and ϕ_t the maximum allowed reactive power demand, in percentage of the active power demand, during the hour t.
- Reserves for primary frequency control: up and down reserves, ur_t and dr_t,
  $$ur_t \geq \sum_{g \in \mathcal{G}} \left(u_{g,t}^{s,d} \cdot P_g^{max} - p_{g,t}^{s,d} \right) + \sum_{bs \in \mathcal{B}} ur_{bs,t}^{s,d} \tag{11}$$
  with $ur_{bs,t}$ the increase in active power that can be provided by BES bs in hour t taking into account the active and reactive power provided and the stored energy. The down reserve is obtained in a similar way.
  Note that only reserve provided by generators and BES devices have been considered, as normal candidates to provide frequency control.

Additional reserves (eg, interruptible loads) can be considered, especially in the case of imposing a minimum load curtailment under demand of the DSO, or as a premise to switch into islanding mode.

E. Deterministic OPF Scheduling Problem (DOPF)

The formulation of the deterministic OPF problem used to determine operational set-points in the short term can be obtained particularizing the stochastic OPF for a specific realization of energy prices, as well as the evolution of demand and photovoltaic generation. Note that the 24-hour ahead energy prices are known, and only the best forecasts for demand and PV generation are considered and updated before each solution of the DOPF to address uncertainties in the short term.

Obviously, similar constraints associated to ancillary services presented for the stochastic OPF can be imposed in the short-term DOPF.

TABLE I
STOCHASTIC 24-HOUR-AHEAD SCHEDULING PROBLEM.

$$\text{Minimize} \quad \sum_{p\in\Omega_p} \mu_p \cdot \left\{ \sum_{s\in\Omega_s} \mu_s \cdot \left[\sum_{d\in\Omega_d} \mu_d \cdot \left(\sum_{t\in\mathcal{H}} \pi_t^p \cdot mp_t^{s,d} + \sum_{g\in\mathcal{G}} C_{g,t}^{s,d}(p_{g,t}^{s,d}) + \sum_{id\in\mathcal{I}} C_{id,t}^{s,d}\left([1-ls_{id,t}^{s,d}]\cdot pe_{id,t}^{d}\right)\right)\right]\right\} \tag{1}$$

Subject to

$$\sum_{g\subset i} p_{g,t}^{s,d} + \sum_{pv\subset i} p_{pv,t}^{s} + \sum_{bs\subset i} (pd_{bs,t}^{s,d} - pc_{bs,t}^{s,d}) - \sum_{ni\subset i} p_{ni,t}^{d} - \sum_{id\subset i} p_{id,t}^{s,d} = \sum_{j\in\mathcal{N}} V_{i,t}^{s,d} \cdot V_{j,t}^{s,d} \left(G_{ij}\cdot\cos\varphi_{ij}^{s,d} + B_{ij}\cdot\sin\varphi_{ij}^{s,d}\right) \quad \forall i, \forall t, s\in\Omega_s, d\in\Omega_d \tag{2}$$

$$\sum_{g\subset i} q_{g,t}^{s,d} + \sum_{bs\subset i} q_{bs,t}^{s,d} - \sum_{ni\subset i} q_{ni,t}^{d} - \sum_{id\subset i} q_{id,t}^{s,d} = \sum_{j} V_{i,t}^{s,d} \cdot V_{j,t}^{s,d} \left(G_{ij}\cdot\sin\varphi_{ij}^{s,d} - B_{ij}\cdot\cos\varphi_{ij}^{s,d}\right) \quad \forall i, \forall t, s\in\Omega_s, d\in\Omega_d \tag{3}$$

$$p_{id,t}^{s,d} = ls_{id,t}^{s,d}\cdot pe_{id,t}^{d} \qquad q_{id,t}^{s,d} = ls_{id,t}^{s,d}\cdot qe_{id,t}^{d} \qquad \forall id, \forall t, s\in\Omega_s, d\in\Omega_d \tag{4}$$

$$V^{min} \le V_{i,t}^{s,d} \le V^{max} \qquad \forall i, \forall t, s\in\Omega_s, d\in\Omega_d \tag{5}$$

$$s_{ij,t}^{s,d} \le S_{ij}^{max} \qquad \forall ij, \forall t, s\in\Omega_s, d\in\Omega_d \tag{6}$$

$$u_{g,t}^{s,d}\cdot P_g^{min} \le p_{g,t}^{s,d} \le u_{g,t}^{s,d}\cdot P_g^{max} \qquad u_{g,t}^{s,d}\cdot Q_g^{min} \le q_{g,t}^{s,d} \le u_{g,t}^{s,d}\cdot Q_g^{max} \qquad \forall g, \forall t, s\in\Omega_s, d\in\Omega_d \tag{7}$$

$$\left(pd_{bs,t}^{s,d} - pc_{bs,t}^{s,d}\right)^2 + \left(q_{bs,t}^{s,d}\right)^2 \le (S_{bs}^{max})^2 \qquad \forall bs, \forall t, s\in\Omega_s, d\in\Omega_d \tag{8}$$

$$soc_{bs,t}^{s,d} = soc_{bs,t-1}^{s,d} + \eta_c\cdot pc_{bs,t}^{s,d} - pd_{bs,t}^{s,d}/\eta_d \qquad SOC_{bs}^{min} \le soc_{bs,t}^{s,d} \le SOC_{bs}^{max} \qquad \forall bs, \forall t, s\in\Omega_s, d\in\Omega_d \tag{9}$$

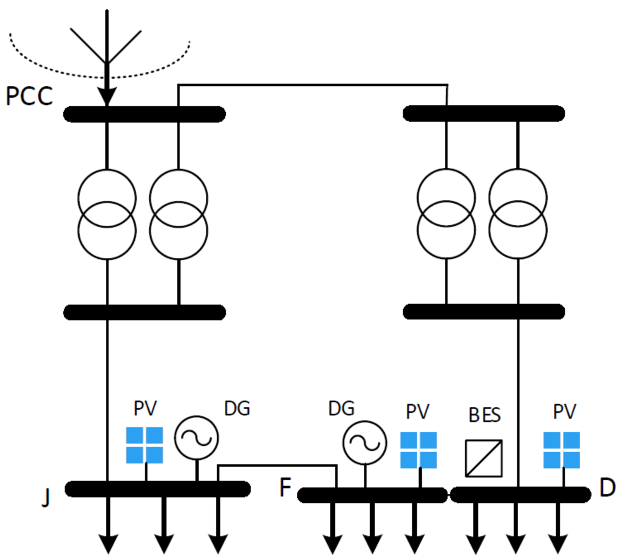

Fig. 1. MCAST Microgrid.

IV. MCAST MICROGRID

The main campus of the Malta College of Arts, Science and Technology (MCAST) includes 64 kWp solar generation, back-up diesel generators and remote monitoring and control of loads (Figure 1). Besides, the installation of a BES device is considered for the future to add flexibility to the microgrid control.

TABLE II
MCAST LOADS & GENERATION RESOURCES.

Building	Device	kW	kvar
D	Load ES	100	19.78
	Load NE	100	10.04
	Load AC	20	-2.01
	PV	21	0
	BES	30 kVA, 40 kWh	
F	Load ES	100	10.04
	Load NE	100	10.04
	Load AC	20	-2.01
	PV	22	0
	Backup generator	100	50
J	Load ES	100	20.31
	Load NE	100	19.78
	Load AC	50	20.07
	PV	21	0
	Backup generator	100	50

Table II summarizes the peak loads and the characteristics of the generation and storage devices used in this study of the MCAST microgrid. The microgrid comprises three buildings with essential (ES), interruptible (NE) and air conditioning loads (AC). Air conditioning loads have been considered interruptible loads. Further details of the MCAST microgrid can be found in [17].

V. NUMERICAL RESULTS

In order to characterize the uncertainty associated to demand and PV generation, hierarchical clustering has been used to identify the number of relevant patterns using data previously

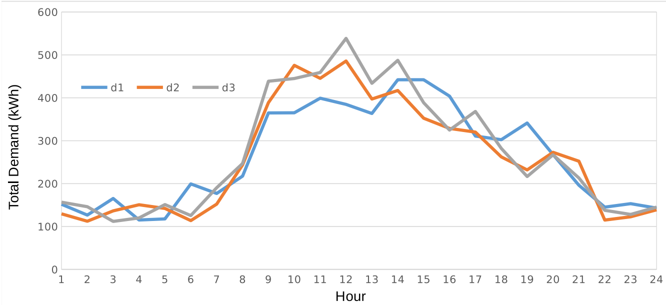

Fig. 2. Demand scenarios.

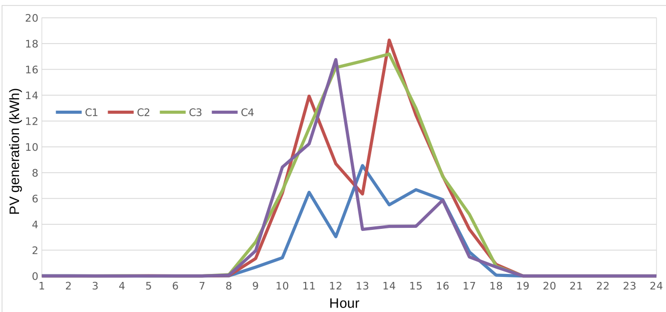

Fig. 3. Photovoltaic generation scenarios.

recorded on weekdays. Then, the assignment of the different time series to each cluster has been refined using a clustering technique based on k-means. Load data recorded during 15 working days have been used to obtain the scenarios presented in Figure 2, with probabilities of 0.4, 0.33 and 0.27 respectively. Similarly, PV generation recorded during 26 days have been used to identify the four PV scenarios presented in Figure 3, with probabilities of 0.154, 0.269, 0.462 and 0.115.

In order to include uncertainty in energy prices, the hourly energy prices of the Spanish Day-Ahead Electricity Market [18] have been used to identify relevant energy price scenarios. The hourly prices of 42 consecutive workdays have been used to obtain the four price scenarios presented in Figure 4, with probabilities of 0.214, 0.286, 0.048 and 0.452, respectively.

Peak loads presented in Table II have scaled to obtain hourly loads scenarios, taking into account the contribution of each

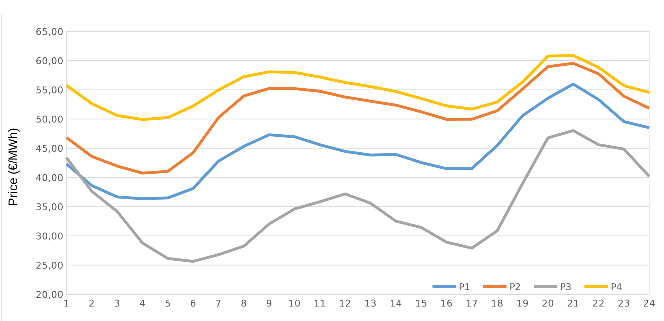

Fig. 4. Hourly energy price scenarios.

individual load to the total load of the microgrid. Similarly, expected hourly PV generations have been obtained for each PV scenario.

A. *Day-Ahead Stochastic OPF*

The SOPF problem presented in Table I have been used to obtain the expected operational costs of the MCAST microgrid, taking into account the uncertainties represented by load, PV generation, and price scenarios presented in Figures 2, 3 and 4. An operating cost of 200 €/MWh has been used for diesel back-up generators, and an instrumental cost of 300 €/MWh has been imposed to load shedding, in order to avoid load curtailment under "normal" energy prices. A 90% efficiency of charge/discharge cicle of the BES device has been considered, leading to a 95% efficiency in the charge and discharge processes.

The expected operational cost for the 24 hours of the scheduling horizon (24-hours ahead stochastic scheduling problem) is 313.5€. This cost is the reference operational cost to be compared with the cost including the provision of ancillary services.

1) Provision of reactive power support: In many electrical systems, consumers are required to maintain a power factor greater than 0.95 in daylight hours (33% of reactive power with respect to active power), prohibiting the injection of reactive power at night hours. This constraint is easily fulfilled without the need for additional actions, given that the loads are locally compensated in terms of power factor. However, if the microgrid reached an agreement with the DSO to maintain the power factor above 0.98 in the daytime hours (20.3% of reactive power with respect to the active power), it would imply a light increase in the expected cost of 0.35% (314.6€ per day), due to the need to start one of the diesel groups to provide reactive power in some low probability cases.

If a greater reactive contribution to the system is needed, with a reactive consumption that does not exceed 10% of reactive power with respect to the active power in daytime hours, the operating cost would increase to 421.9 € per day (a noticeable 34.6% increase), due to the need to start a diesel group between 9:00 and 17:00 in some scenarios. This increase would point to the need to adopt improvements in the microgrid that would reduce the cost in the provision of the ancillary service, such as a new capacitor bank in the PCC or the provision of reactive power by the inverters of the PV plants.

2) Provision of frequency control: Suppose that the microgrid reaches an agreement with the TSO to provide primary frequency control through the available resources, ie, diesel generators and BES resources (PV generation could also provide frequency control, but it has not been considered in this study). This contract implies the need to maintain a minimum power reserves in such devices, in order to respond to changes in the frequency of the system. If a power margin were imposed of $\pm$25 kW with respect to the normal working point of the microgrid, the expected cost would increase to

313.7€ per day, a light increase as the reserve is mainly provided by the BES.

If a greater margin of power contribution to the system is needed, about 50 MW, the operating cost would increase to 379.4€ per day (21% increase), with the impossibility of providing the required reserve in certain scenarios due to generator limits.

B. Short-term Deterministic OPF

In order to compare with the expected operational costs presented above, the DOPF problem have been used to obtain operational costs for certain realizations of the uncertainty scenarios. Suppose that the energy prices are represented by P4 series, and that demand and PV generation follow the evolution represented by series D3 and C3 respectively. In this case, the expected operational cost for the 24 hours of the scheduling horizon (24-hours ahead deterministic scheduling problem) is 347.5 €. This cost is to be compared with the cost including the provision of ancillary services under deterministic conditions:

1) Provision of reactive power support: The microgrid is able to accomplish with a power factor greater than 0.95 in daylight hours (33% of reactive power with respect to active power). However, if a minimum power factor of 0.98 in the daytime hours is imposed, there is no increase in cost as the reactive power support would be provided by the BES.

If a limit of 10% of reactive power with respect to the active power in daytime hours was imposed (power factor above 0.995), the operating cost would increase to 425.1€ per day (an increase of 22.3%), due to the need to start a diesel group between 9:00 am and 5:00 pm.

2) Provision of frequency control: If a power margin were imposed of ± 25 kW, the cost would increase to 347.6€ per day, an insignificant increase due to the fact that all reserve is provided by the BES. A reserve margin of 50 MW would result in an infeasible problem, due to the minimum generation imposed by the diesel generators when started-up.

The inclusion of load shedding in the reserves, as an additional control action if required (eg, to go into islanding operation), would increase the reserve margin to 70 kW up and 35 kW down, without any increment of the operational cost.

VI. Conclusions

This paper has presented the optimization problems used to determine the set-points of controlled resources in a microgrid, both in a stochastic formulation for the day-ahead scheduling problem, and the deterministic formulation for the real-time scheduling. Constraints associated to the provision of Ancillary Services such as frequency control support, voltage control support, and congestion management have also been presented and discussed.

Results of the optimization of the MCAST pilot microgrid of the 3DMicroGrid project are presented, quantifying the effect of the provision of ancillary services in the expected operational costs.

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