Comparative Study of Energy Management Strategies in Collaborative Microgrids of Domestic Prosumers

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***Abstract*—An optimization model is proposed to manage a residential microgrid including a charging spot with a vehicle-to-grid system and renewable energy sources. We consider the microgrid operated in grid-connected mode. The model is executed one-day-ahead and generates a schedule for all components of the microgrid. The microgrids are ubicated in Xermade, Galicia, Spain.**

Keywords—Optimal management, prosumers, microgrid, smart grid, renewable generation, collaborative.

NOTATION

Set			
m	Set of year months	**Uw**	Set of hours that the EV is connected in the house
h	Set of day hours	**NotUw**	Set of hours that the EV is not connected in the house
Parameter			
$\bar{P}^{PV}_{m,h}$	Maximum solar power [kW]	ξ	Charging efficiency of battery bank and EV [%]
$\bar{P}^{W}_{m,h}$	Maximum wind power [kW]	N^{EV}	EV battery capacity [kWh]
$P^{D}_{m,h}$	Electric demand power [kW]	N^{B}	Battery bank capacity [kWh]
SOC^{ini}	Initial State of Charge of the Electric Vehicle battery and bank of batteries [%]	$D^{EV}_{m,h}$	EV electric demand power [kW]
$\overline{SOC}$	Maximum state of charge of EV and battery bank [%]	P^{I}	Grid capacity [kW]
$\underline{SOC}$	Minimum state of charge of EV and battery bank [%]	$C^{I_1}_{h}$	Electricity price [€/kWh]
a	EV battery and bank of batteries technical parameter [%]	C^{I_2}	Interconnection cost for capacity [€/kWh]
η	Discharging efficiency of battery bank and EV [%]		
Variables			
$SOC^{EV}_{m,h}$	EV Stat of Charge [%]	$P^{W}_{m,h}$	Wind power generation [kW]
$SOC^{B}_{m,h}$	Bank battery Stat of Charge [%]	$P^{PV}_{m,h}$	Photovoltaic power generation [kW]
$P^{EV,d}_{m,h}$	EV discharging rate [kW]	$P^{SG}_{m,h}$	Power sold to the grid [kW]
$P^{B,d}_{m,h}$	Battery bank discharging rate [kW]	$P^{PG}_{m,h}$	Power purchased from the grid [kW]
$P^{EV,c}_{m,h}$	EV charging rate [kW]	$x^{EV}_{m,h}$	Power flow direction in the EV battery
$P^{B,c}_{m,h}$	Battery bank charging rate [kW]	$x^{B}_{m,h}$	Power flow direction in the battery bank
$P^{EV}_{m,h}$	EV Stat of Charge [kW]	$x^{CP}_{m,h}$	Connection state in charging point of the EV
$P^{B}_{m,h}$	Battery bank Stat of Charge [kW]	$x^{IP}_{m,h}$	Power flow direction in the interconnection

I. INTRODUCTION

DUE to the current development of renewable sources of energy, the integration of it in the optimal management of residential energy systems will become a real need in the medium term [1]. Smart-houses are going to be the next step in the distribution energy resources framework [2]. This work will include what is called a residential microgrid, which could contain different generation resources, storage devices and an electric consumption. The most common line of research in residential microgrids is the introduction of an optimal demand response system which exploits the demand elasticity and its management through a storage system.

In this paper, authors are proposing two types of microgrids management. First of all, we will study the microgrid management of two microgrids working autonomously; then, we will study the microgrid management when microgrids are working collaborative. Moreover, we are introducing the electric vehicle (EV) in the microgrid management. It is important the role that will play the EV because of it is penetrating heavily in our society in the recent years.

II. MICROGRID DESCRIPTION

A. *Microgrid Control*

The operation and management of the microgrid is focused in the minimization of the economic cost of the operation of the microgrid. The system takes advantage of price differences between the peak and off-peak periods of the day and maximizes the use of the renewable energy sources. Daily forecasts regarding weather and demand are used as an input together with the energy price offered by the energy retailer. The final result is the optimal energy schedule for each type day of every month of the year.

A. Microgrid Components

The residential microgrids considered for this work correspond two households (prosumers) described in Fig 1. In addition, the differences between the two households are described in Table I. One the one hand, the first prosumer is in a house where two adults live. On the other, the second prosumer under study is a house where live two adults, one child and one teenager.

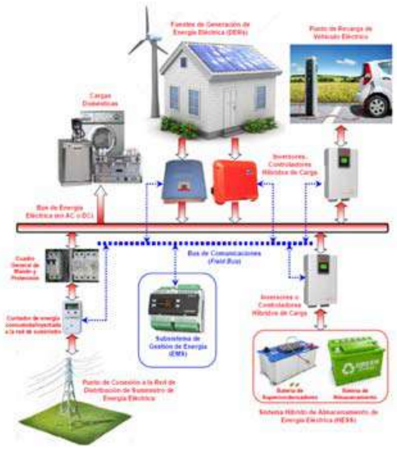

Fig. 1. Conceptual block diagram of the structure of a domestic microgrid around a domestic prosumer

TABLE I
DIFFERENCES BETWEEN HOUSEHOLDS

	Case 1	Case 2
Renewable generation	Photovoltaic Modules	Mini Wind
Storage system	Battery bank	Battery bank
EV	Yes	Yes

III. MATHEMATICAL MODEL

The microgrid described is managed by means of an optimization algorithm. This algorithm is based on a mathematical programming that takes into account the technical restrictions of all the elements included and minimizes the total cost of the system.

A. Electric Vehicle

The key aspects of EV modeling is the performance of the battery with the user's needs. The battery life of the EV depends on the charge and discharge cycles of the battery. Fig. 2 shows the function of the action of the EV battery and the battery bank. It is noted that the battery can be charged or discharged between two limits, the minimum and the maximum charge levels. On the other hand, between the minimum SOC and the limit *a*, the discharge is limited by a linear function which depends on the specific SOC [3].

Equations 1 – 3 define the power limits for both processes (charging and discharging) for the EV battery bank:

$$0 \leq P_{m,h}^{EV,c} \leq N^{EV} \cdot x_{m,h}^{EV} \; \forall h \in U_w \tag{1.1}$$

$$0 \leq P_{m,h}^{B,c} \leq N^{B} \tag{1.2}$$

$$0 \leq P_{m,h}^{EV,d} \leq N^{EV} \cdot \left(1 - x_{m,h}^{EV}\right) \forall h \in U_w \tag{2.1}$$

$$0 \leq P_{m,h}^{B,d} \tag{2.2}$$

$$P_{m,h}^{EV,d} \leq \frac{N^{EV}}{a - \underline{SOC}} \cdot SOC_{m,h}^{EV} \; \forall h \in U_w \tag{3.1}$$

$$P_{m,h}^{B,d} \leq \frac{N^{B}}{a - \underline{SOC}} \cdot SOC_{m,h}^{B} \tag{3.2}$$

where $x_{m,h}^{EV}$ is a binary variable that expresses the state of charge/discharge of the EV battery; if $x_{m,h}^{EV} = 1$ if the EV battery is charging, if it is equal to 0 it does not charge. $0 \leq P_{m,h}^{EV,c}$, and $0 \leq P_{m,h}^{EV,d}$ represent the charged and unloaded power of the EV, respectively, the same goes for the bank of batteries. On the other hand, equations (4.1) and (4.2) show the energy used by the EV when it is not connected to the microgrid.

$$P_{m,h}^{EV} \begin{cases} \left(\xi \, P_{m,h}^{EV\,c} - \frac{P_{m,h}^{EV\,d}}{\eta}\right) \Delta_T \;\; si \; h \in U_w \\ -D_{m,h}^{EV} \qquad si \; h \in NotU_w \end{cases} \tag{4.1}$$

$$P_{m,h}^{B} = \left(\xi \, P_{m,h}^{B\,c} - \frac{P_{m,h}^{B\,d}}{\eta}\right) \Delta_T \tag{4.2}$$

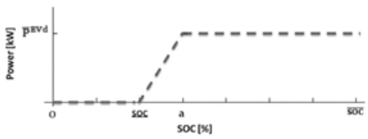

Fig. 2. Power limit for the battery discharging process

The state of charge is defined by equations from (5) to (8):

$$N^{EV} SOC_{m,h}^{EV} = N^{EV} SOC_{m,h-1}^{EV} + P_{m,h-1}^{EV} \tag{5}$$

$$N^{B} SOC_{m,h}^{B} = N^{B} SOC_{m,h-1}^{B} + P_{m,h-1}^{B} \tag{6}$$

$$\underline{SOC} \leq SOC_{m,h}^{EV} \leq \overline{SOC} \tag{7}$$

$$\underline{SOC} \leq SOC_{m,h}^{B} \leq \overline{SOC}, \tag{8}$$

where $SOC_{m,h-1}$ is the initial SOC if it is the first instant of time.

Finally, the battery charge can only be positive, according to (9) and (10):

$$0 \leq P_{m,h}^{SG} \leq \overline{P}^{I} x_t^{IP} \tag{9}$$

$$0 \leq P_{m,h}^{PG} \leq \overline{P}^{I} (1 - x_t^{IP}), \tag{10}$$

where $x_t^{IP} = 1$ if the microgrid is selling the excess power, and is 0 where the microgrid is fed.

B. Renewable Sources

Renewable energy sources depend on the weather of each day and, therefore, a type profile can be established but it will never be totally true. In the programming of this microgrid, photovoltaic and wind energy have been used. In order to program this mathematical algorithm, some type profiles of photovoltaic and wind production have been established. The equations that govern the use of it are (11) and (12).

$$P_t^{W} = \overline{P}_{m,h}^{W} \tag{11}$$

$$P_{m,h}^{PV} = \overline{P}_{m,h}^{PV} \tag{12}$$

C. Power Balance

So that the demand corresponds to the production, it is necessary to create the power balance which is represented by the expression (13). On its left side the total power available in the microgrid is represented in each period of time while in its right side represents the demand during the same period:

$$P^{W}_{m,h} + P^{PV}_{m,h} + P^{EV\,d}_{m,h} + P^{B\,d}_{m,h} + P^{PG}_{m,h} = P^{D}_{m,h} + P^{EV\,c}_{m,h} + P^{B\,c}_{m,h} + P^{SG}_{m,h} \quad (13)$$

D. Objective Function

The purpose is the minimization of the economic cost associated with the electricity demand of a house. The total cost is the minimum of the sum of equations 14 and 15.

$$C_1 = \sum C^{l_2} \cdot \left(P^{PG}_{m,h} + P^{SG}_{m,h}\right) \quad (14)$$

$$C_2 = \sum C_h^{l_1} P^{PG}_{m,h} - \sum C_h^{l_1} P^{SG}_{m,h} \quad (15)$$

$$C_{TOT} = C_1 + C_2 \quad (16)$$

E. Prosumers Working Collaboratively

The model that is established is simply a modification of the previous one. The restrictions between (1) and (12) have been programmed twice, that is, once for each case. Equation (13) adds, on both sides of the match, the specific terms in (13) for both cases. The same happens in equations (14) and (15), verify the powers purchased and sold to the electricity distribution network for both cases.

IV. Parameters

The values of the different parameters to be entered are shown in Table II. It should be mentioned that not all cases make use of all of them; only those parameters of the devices that make up the micro-network, which have been described above, must be entered.

TABLE II
PARAMETERS TO BE ENTERED

SOC^{ini}	50 %	ξ	99 %
$\overline{SOC}$	100 %	N^{EV}	35,4 *kWh*
$\underline{SOC}$	30 %	N^{B}	5 *kWh*
a	40 %	P^{I}	6,6 *kW*

The electric consumption profiles are shown in Fig. 3 and 4 [4]-[5].

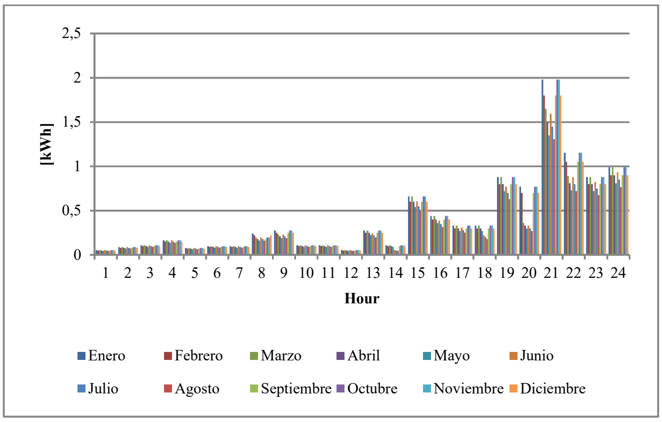

Fig. 3. Prosumer #1's consumption profile (a house with two adults)

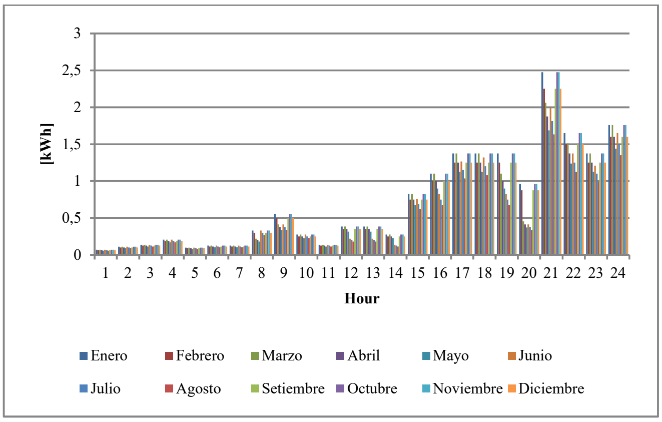

Fig. 4. Prosumer #2's consumption profile (a house with two adults, one child and one teenager)

As an example of the generation profiles, table III shows the PV generation for Prosumer #1.

TABLE III
PV GENERATION PROFILE A

Hour	January	February	March	April	May	June
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	2,59	0,01	0,62
7	0	0	0	26,01	12,35	15,52
8	0	0	4,29	69,83	37,49	34,58
9	0	14,38	42,02	114,78	87,81	80,57
10	38,72	43,91	90,61	155,43	130,75	113,34
11	60,12	85,42	137,67	217,74	198,81	149,31
12	91,28	112,56	162,99	246,79	221,28	186,16
13	95,85	110,97	185,73	210,14	234,12	223,65
14	91,37	110,17	202,57	186,68	219,73	219,86
15	102,15	125,18	161,03	168,71	210,80	193,49
16	81,35	101,66	126,70	118,25	167,64	177,40
17	44,11	63,39	108,25	64,19	127,74	140,23
18	0,83	25,35	49,46	19,57	75,89	85,58
19	0	0	5,35	0,02	26,37	36,89
20	0	0	0	0	3,80	7,92
21	0	0	0	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0

V. Simulation Results

From the resolution of the algorithm previously raised, the corresponding results were obtained for each demand and generation case raised. For such analysis of these results, proceed to the graphic presentation of the balance of hourly powers of the most representative months for each case. However, we will analyze each month power balance equation.

In the graphs below, *PPV* is the photovoltaic power, *PSG* is the power sold to the conventional grid, *PPG* is the power purchased from the conventional grid, *PEV_D* and *PEV_C* are the discharge and load powers of the electric car battery (*EV*), *PB_D* and *PB_C* are, also, the discharge and charge powers of the battery bank; finally, *PD* is the power demanded by the house.

A. *Prosumer 1: Two Adults*

As you can see in the graphs shown in Fig. 5, the power balance is net at every hour of the day. In this figure, the power flow for the month of January is represented.

B. *Prosumer 2: Two Adults, One child and One Teenager*

As it can be seen in the graphs shown in Fig. 6, the power balance is net at every hour of the day. Unlike in the previous case, here the micro-network management pattern is not so repetitive. Wind generation, a difference from photovoltaics, occurs during all hours of the day and, therefore, the household's energy needs are met through it. On the other hand, the charge and discharge of the battery bank is constant during all hours of the day. It is possible to specify the month of October where the wind generation is significantly lower than the rest of the months of the year and, therefore, the charges and discharges of the battery bank are not as pronounced.

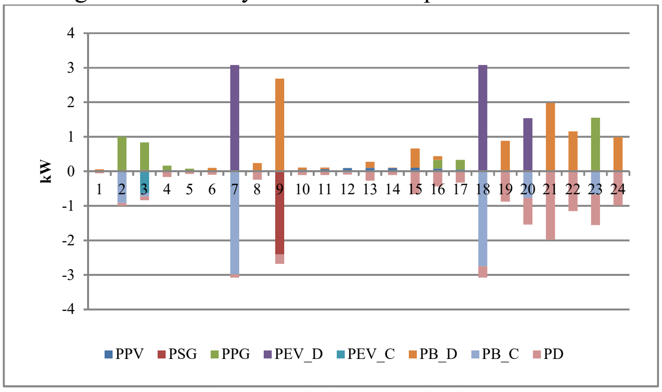

Fig. 5. Prosumer #1's profile Power balance. Month of January

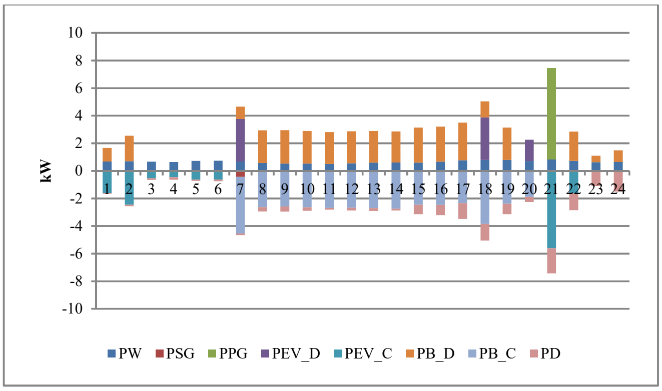

Fig. 6. Prosumer #2's profile Power balance. Month of July

It can be seen that most of the energy needs of the home are supplied by means of energy from the renewable sources considered. In addition, there is a large amount of energy produced that is sold to the electric power supply distribution network.

C. *Results Comparison*

From the simulation of both types of configurations, it can be clearly seen that the purchase of energy from the power supply distribution network when the microgrids work collaboratively is much smaller than when they work independently. It can also be seen that the sale of energy to the distribution network of electricity supply is notoriously greater when the networks collaboratively than when they do so independently. On the other hand, you will see that the use of battery banks is very important since they significantly decrease the purchase of red energy. It is important to note that it has not been imposed in the programming of the model that you can buy energy from the grid when it is cheaper and, when it goes up in price, sell it. Therefore, energy flows would change.

VI. CONCLUSIONS

Thanks to the programming of an energy management model of a microgrid it can be estimated whether or not a renewable energy generation facility is optimal. In this case, the feasibility of a mini-wind installation and a photovoltaic installation has been analyzed.

We have seen how the power balances were met at all times of the day and analyzed the power flows. On the other hand, we have seen how act the EV battery in the microgrid.

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