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Availability of Household loads to Participate in Demand Response

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***Abstract*—This paper proposes a novel method to characterize the availability of household loads to participate in demand response programmes, as well as detailed mathematical models to characterize households loads. The availability of the households results from the flexibility of their controllable loads to increase/reduce consumption. This flexibility is calculated taking into account the comfort levels predefined by the customers and the technical restrictions of the controllable loads. The proposed method was evaluated through a management algorithm developed to perform demand control actions in quasi-real-time, according to the objectives of the distribution system operator or energy aggregator and the availability of the household loads. A scenario with a single household located in a semi-urban area is used to illustrate the application of the algorithm and validate the proposed method.**

Keywords: Controllable loads, Demand response, Households Flexibility, Physically-based load models

I. Introduction

The rising share of energy generated by renewable sources is increasing the volatility of the energy generation sector. Large conventional plants (thermal and others) have to be kept in the system, in order to balance the oscillations of the generation pattern of distributed generators. The decrease in the controllability of the electricity generation brings new challenges for the operation of power systems. In this context, the concepts of Demand Response (DR) and Demand Side Management gain strength, since they are seen as inevitable to help maintain the balance between demand and supply [1]. With this objective, Callaway in [2] proposed a model to control the aggregated power from a population of Thermostatically Controlled Loads (TCL), through the adjustment of temperature set points. A similar work was proposed in [3], with the objective of regulating the aggregated power of the TCL.

Moreover, DR programs can be used to help electricity markets becoming more efficient and competitive [4, 5], through the adoption of real-time (hourly) prices. In fact, real-time pricing will allow consumers to adjust their energy consumptions, with the objective of minimizing their electricity bill [6, 7].

In the context of smart grids, DR is a key functionality that will improve energy efficiency and increase global reliability of power systems [1]. In order to know the potential of the households to participate in DR, it is necessary to develop methods to calculate their availability. Heleno et al. [8] proposed a methodology to characterize the availability of thermal appliances to provide reserve services. The method considers information collected 24 hours in advance, such as consumption habits and comfort patterns related with the appliances operation.

This paper presents a novel method to characterize the availability of household loads to participate in DR. The method considers information in quasi-real-time, such as outdoor temperatures, consumption habits and comfort patterns related with the controllable loads.

The availability of the households is calculated by a local controller installed at the customer's site – the Home Energy Manager (HEM), which takes into account the flexibility of all controllable loads to reduce/increase their consumption.

The feasibility of the proposed method is evaluated through a management algorithm developed to perform demand control actions in quasi-real-time, according to the availability of the households and objectives of the Distribution System Operator (DSO) or Aggregator. For the purpose of this work, the term "quasi-real-time" is used in the sense of monitoring and managing controllable loads in short periods of time (time periods of 5 minutes were assumed). The referred algorithm uses TCL (such as electric water heaters, air conditioners and refrigerators) as well as Electric Vehicles (EV) to simulate load control actions. Physically-Based Load Models are used to simulate the TCL. For EV, assumptions regarding the power consumption and State-Of-Charge (SOC) control conditions are considered.

A case study of a single household located in a semi-urban area of Porto (Portugal) was used in order to evaluate algorithm developed.

II. Home Energy Manager Framework

The HEM is a local controller installed at the customer's site, whose mainly functions are monitoring and managing controllable loads, according to customer preferences. In addition, the HEM has the capability of establishing bidirectional communications with a DSO/Aggregator, in order to perform demand control actions. Note that the HEM also can be endowed with functionalities to monitor uncontrollable loads and microgeneration sources. In this work, these functionalities were not considered.

The HEM framework is presented in Fig.1.

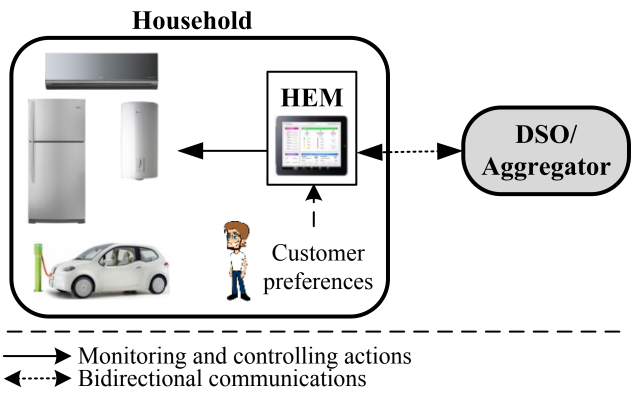

Fig. 1. Home Energy Manager framework

The feasibility of the proposed framework was evaluated using a management algorithm divided in three phases (Fig. 2). The first phase consists on defining the flexibility of the households to reduce/increase load, for the time step (t+1) – these calculation are performed by the HEM. The flexibility is calculated according to the comfort levels predefined by the user and the technical constraints of the controllable loads.

Afterwards this information is sent to a DSO/Aggregator that may use this information to adjust the load of the households. If the DSO/Aggregator decides to perform control actions, it will send a power set point to each household, in order to define the total consumption of the controllable loads (phase two), for the time step (t+1).

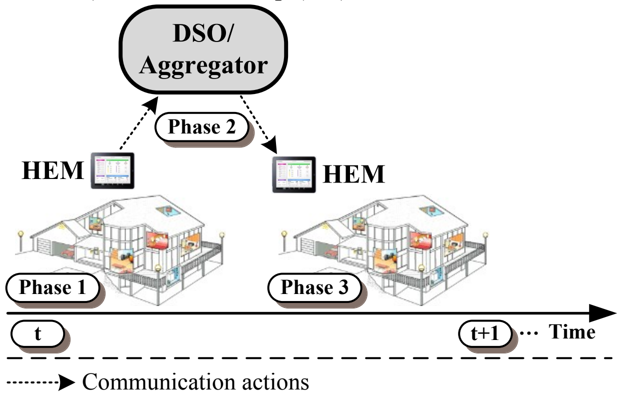

Fig. 2. Management algorithm framework

According to the information sent by the DSO/Aggregator the HEM runs an algorithm that defines the power that each controllable load will consume in time step (t+1). For this purpose, an optimization algorithm is used, which takes into account the requirements predefined by the customer and the technical limitations of the controllable loads (phase three). In order to enforce these power values, the HEM sends control signals to the controllable loads. This cycle is successively repeated.

Based on this framework, two different states of operation can be identified: regular operation and DR operation. In regular operation, the controllable loads consume energy without being subjected to any control action by the DSO/Aggregator. In DR operation, the controllable loads consume energy according to power set points sent by the DSO/Aggregator.

III. Load Models

The power and energy consumption of the controllable loads is calculated through the adoption of load models that take into account the customers' habits and several daily events, such as the time at which the consumer takes a shower, the room set point temperature or the time at which the consumer leaves/arrives home. Other physical aspects, such as building design, constructive characteristics and outdoor temperature, also influence the behaviour of the controllable loads.

In order to perform demand control actions, loads such as Electric Water Heaters (EWH), Air Conditioning (AC), refrigerators or EV were considered. The TCL were modelled through physically-based load models that define the operation state of the appliances according to their physical characteristics, external temperatures and internal temperatures defined by the household owner. Conversely, assumptions regarding the power required to be supplied and grid connection period were made in order to define EV energy consumption.

The models used for the controllable loads characterisation in regular operation and DR operation are described in detail in the next subsections

A. In Regular Operation

In order to simulate the behaviour of an AC, an inverter system was chosen, since it can regulate the temperature with fewer oscillations and is more efficient than traditional AC system. Other relevant aspect is its capacity to assume continuous power rates, instead of just being on or off. The inverter AC regulates the temperature (θ_t) of the room by a thermostat and inverter system that speed up or slows down the compressor, in order to reach the temperature set point (θ^s).

In regular operation, the behaviour of the inverter AC for cooling is described by the following mathematical model, developed according to the thermal equation presented in [3].

$$\theta_{t+1} = \theta_t - \frac{\Delta t}{CR}(\theta_t - \theta_t^o + RP_t\eta + w_t) \quad (1)$$

$$P^{Var} = \frac{(\theta_{t+1} - \theta^s)C}{\Delta t \cdot \eta} - \frac{\theta_{t+1} - \theta_t^o + w_t}{R \cdot \eta} \quad (2)$$

$$P_{t+1} = \begin{cases} P^{Max}, & if\ P^{Var} > P^{Max} \\ P^{Min}, & if\ P^{Var} < P^{Min} \\ P^{Var}, & otherwise \end{cases} \quad (3)$$

The index t defines time and $\Delta t(h)$ the time elapsed per step. The parameter θ_t^o (°C) is the outdoor temperature. C ($kWh/$°C) is the thermal capacitance and R (°C$/kW$) is the thermal resistance of the room being air-conditioned. The term $P_t\eta$ (kW) governs the rate of thermal energy transfer, due to the operation of the inverter AC. This term results from the multiplication of the electric power P_t (kW) by the coefficient of performance (η). w_t is a noise process accounting for all heat gain and loss not modelled, which results from solar gains, opening and closing doors and operation of other loads.

The parameters P^{Max} and $P^{Min}(kW)$ define the maximum and minimum electric power of the inverter AC. While $P^{Var}(kW)$ represents the rates of power that the inverter AC can assume, in order to reach the temperature set point.

Similar thermal equations were used to characterize the behaviour of the EWH and refrigerators. However, instead of operating in continuous mode, these appliances regulate their internal temperature through a thermostat and relay actuator with state $m_t \in \{0,1\}$ that determines whether the compressor is switched on (m=1) or off (m=0), according to a predefined temperature set point (θ^s) and temperature dead band (δ).

In case of the EWH, its behaviour is described by a thermal equation proposed in [9] by Chong and Debs. However, instead of a resistance, it includes a heat loss constant α $(kW/°C)$. Additionally, the term v_t $(kW/°C)$ is added to the model, in order to represent the hot water consumption. The heat loss due to hot water consumption is calculated taking into account the difference between the temperature desired for hot water usage (θ^d) and the tank water inlet temperature (θ^w). In regular operation, the behaviour of the EWH is described by the following mathematical model.

$$\theta_{t+1} = \theta_t + \frac{\Delta t}{C}\left(-\alpha\left(\theta_t - \theta^i\right) - v_t\left(\theta^d - \theta^w\right) + m_t P\right) \tag{4}$$

$$m_{t+1} = \begin{cases} 0, & if\ \theta_t > \theta^s + \frac{\delta}{2} \\ 1, & if\ \theta_t < \theta^s - \frac{\delta}{2} \\ m_t, & otherwise \end{cases} \tag{5}$$

In order to describe the behaviour of a single refrigerator, it was used a thermal equation presented in [10], which has an exponential form. In regular operation, the behaviour of the refrigerator is described by the following mathematical model.

$$\theta_{t+1} = \varepsilon\theta_t + (1-\varepsilon)\left(\theta^i - m_t R P \eta\right)\ with\ \varepsilon = e^{-\frac{\Delta t}{RC}} \tag{6}$$

$$m_{t+1} = \begin{cases} 1, & if\ \theta_t > \theta^s + \frac{\delta}{2} \\ 0, & if\ \theta_t < \theta^s - \frac{\delta}{2} \\ m_t, & otherwise \end{cases} \tag{7}$$

Instead of considering the outdoor temperature as in (1), this model uses the indoor temperature (θ^i) of the room.

In relation to the EV, this charging behaviour was characterized by a mathematical model that takes into account assumptions regarding the power $P_t(kW)$ required to be supplied and state-of-charge control conditions. Instead of thermal capacitance considered in thermal loads, the EV model includes the battery capacity $- BC$ (kWh). Moreover, the parameter η is added to the model, with the objective of representing the efficiency of the EV charging process.

$$SOC_{t+1} = SOC_t + \frac{\eta P_t}{BC}\Delta t \tag{8}$$

$$P^{Var} = \frac{(SOC^{Max} - SOC_{t+1})BC}{\eta\Delta t} \tag{9}$$

$$P_{t+1} = \begin{cases} P^{Max}, & if\ P^{Var} > P^{Max} \\ P^{Min}, & if\ P^{Var} < P^{Min} \\ P^{Var}, & otherwise \end{cases} \tag{10}$$

In regular operation, it is assumed that all the EV owners are completely free to connect and charge their vehicles after arriving home and connecting them to the electricity grid. The EV will charge until they reach the maximum state-of-charge (SOC^{Max}) or are disconnected from the grid by their owners.

B. In Demand Response Operation

The load models previously referred simulate the behaviour of the TCL and EV in regular operation. In DR operation, the controllable loads will be controlled by the HEM. Based on information sent by the DSO/Aggregator, the HEM runs an optimization algorithm that defines the consumption of each TCL and EV for the next time step $(t+1)$. This optimization algorithm takes into account the flexibility of all controllable loads.

As referred, the consumption values are enforced by the HEM through control signals sent to the controllable loads. The control signals specify the operation states (m_t) and power rates (P_t) of the controllable loads.

The behaviour of the refrigerator and EWH is defined by equations (4) and (6), according to the operation states set by the HEM, whereas the behaviour of the inverter AC and EV is set by equations (1) and (8), based on the power rates defined by the HEM.

IV. AVAILABILITY

As referred, the DSO/Aggregator has the capability of managing the flexibility of the consumers. To forecast their availability to reduce/increase load, the DSO/Aggregator relies on the HEM. The HEM is responsible for forecasting the availability of the controllable loads for the time step (t+1), according to the technical limitations of the controllable loads and the levels of comfort defined by the client. The flexibility of the controllable loads was calculated through the manipulation of the mathematical models developed in the previous subsection.

The mathematical model that represents the flexibility to increase/reduce power of the inverter AC $\left(F_{t+1}^{Max}/F_{t+1}^{Min} - kW\right)$ is described by the following equations:

$$Np^{Max} = \frac{(\theta_{t+1} - \theta^{Min})C}{\eta \cdot \Delta t} - \frac{\theta_{t+1} - \theta_t^o}{\eta \cdot R} \tag{11}$$

$$Np^{Min} = \frac{(\theta_{t+1} - \theta^{Max})C}{\eta \cdot \Delta t} - \frac{\theta_{t+1} - \theta_t^o}{\eta \cdot R} \tag{12}$$

$$F_{t+1}^{Max} = \begin{cases} P^{Max}, & if\ Np^{Max} > P^{Max} \\ P^{Min}, & if\ Np^{Max} < P^{Min} \\ Np^{Max}, & otherwise \end{cases} \tag{13}$$

$$F_{t+1}^{Min} = \begin{cases} P^{Max}, & if\ Np^{Min} > P^{Max} \\ P^{Min}, & if\ Np^{Min} < P^{Min} \\ Np^{Min}, & otherwise \end{cases} \tag{14}$$

The parameters θ^{Max} and θ^{Min} (°C) represent the interval of thermal comfort defined by the consumer, in order to provide flexibility to the HEM to reduce/increase load. Np^{Max} and Np^{Min} (kW) represents the necessary power that the appliance needs to match the temperatures θ^{Min} and θ^{Max}, respectively. Thus, the minimum and maximum flexibility is represent by F_{t+1}^{Min} and F_{t+1}^{Max}.

Similar mathematical models were developed and used to forecast the availability to reduce/increase load of the EWH and refrigerator. The mathematical model that defines the flexibility of the EWH is described by the following equations.

$$Np^{Max} = \alpha(\theta_{t+1} - \theta^i) + v_t(\theta^d - \theta^w) + \frac{(\theta^{Max} - \theta_{t+1})C}{\Delta t} \quad (15)$$

$$Np^{Min} = \alpha(\theta_{t+1} - \theta^i) + v_t(\theta^d - \theta^w) + \frac{(\theta^{Min} - \theta_{t+1})C}{\Delta t} \quad (16)$$

$$F_{t+1}^{Max} = \begin{cases} P, & if\ Np^{Max} \geq P \\ 0, & otherwise \end{cases} \quad (17)$$

$$F_{t+1}^{Min} = \begin{cases} P, & if\ Np^{Min} > 0 \\ 0, & otherwise \end{cases} \quad (18)$$

The temperatures θ^{Min} and θ^{Max} establish the thermal availability of the EWH, which defines its electric power flexibility. The parameter $P\ (kW)$ represents the electric power of the EWH. The flexibility of the refrigerator is calculated through equations (17) and (18) in conjugation with the following equations.

$$Np^{Max} = \frac{\varepsilon\theta_{t+1} + (1-\varepsilon)\theta^i - \theta^{Min}}{\eta(1-\varepsilon)R} \quad with\ \varepsilon = e^{-\frac{\Delta t}{RC}} \quad (19)$$

$$Np^{Min} = \frac{\varepsilon\theta_{t+1} + (1-\varepsilon)\theta^i - \theta^{Max}}{\eta(1-\varepsilon)R} \quad (20)$$

In case of the EV, this flexibility is calculated taking into account its maximum state-of-charge and the time step at the EV disconnects from the household (td). This flexibility is calculated through equations (13) and (14) in conjugation with the following equations.

$$Np^{Max} = \frac{(SOC^{Max} - SOC_{t+1})BC}{\eta\Delta t} \quad (21)$$

$$Np^{Min} = \frac{(SOC^{Max} - SOC_{t+1})BC}{\eta\Delta t} - (td - (t+2))\eta P^{Max} \quad (22)$$

Finally, in order to define the overall availability of the client, it is necessary to sum the minimum and maximum flexibility of all controllable loads. Afterwards, this information will be sent to the EA.

V. Optimization Algorithm

Based on the power set point sent by the DSO/Aggregator, the HEM runs an optimization algorithm which defines the power that each controllable load will consume. For this purpose, the following optimization algorithm was developed:

$$Min\ \left|PSP_{t+1} - \left(\sum_{i=1}^{nc} P_{t+1,i}^{CCL} + \sum_{j=1}^{nd} m_{t+1,j} P_j^{DCL}\right)\right| \quad (23)$$

$$Subject\ to$$

$$F_{t+1,i}^{Min} \leq P_{t+1,i}^{CCL} \leq F_{t+1,i}^{Max} \qquad i = 1, \ldots .nc \quad (24)$$

$$m_{t+1,j} \in \left\{\frac{F_{t+1,j}^{Min}}{P_j^{DCL}}, \frac{F_{t+1,j}^{Max}}{P_j^{DCL}}\right\} \qquad j = 1, \ldots .nd \quad (25)$$

The indexes i and j represent the continuous controllable loads (Inverter AC/ EV) and the discrete controllable loads (EWH/refrigerator), respectively. nc and nd represent the number of continuous controllable loads and discrete controllable loads, respectively. The parameter $PSP_{t+1}\ (kW)$ represents the power set point sent by the DSO/Aggregator that defines the total power of the controllable loads, for time step (t+1). The parameter $P_j^{DCL}\ (kW)$ defines the power of the discrete controllable loads. $m_{t+1,j}$ (0 or 1) is the decision variable that defines the state of the discrete controllable loads. $P_{t+1,i}^{CCL}\ (kW)$ is the decision variable that defines the power of continuous controllable loads. Constraints (24) and (25) prevent that the decision variables exceed their limits of flexibility, represented by $[F_{t+1,i}^{Min}, F_{t+1,i}^{Max}]$ and $\left\{\frac{F_{t+1,j}^{Min}}{P_j^{DCL}}, \frac{F_{t+1,j}^{Max}}{P_j^{DCL}}\right\}$.

The optimization problem presented above is convex. In order to make him solvable through Linear Programming, its formulation was changed using the method described in [11].

VI. Case Study

A. Description

The HEM framework and algorithm were tested for a scenario with a single household, located in a semi-urban area in Porto (Portugal). One summer weekday was considered (real outdoor temperatures in Porto on 26th July 2013 were used - Fig. 6), in order to evaluate the potential of the household to participate in DR programs.

The household is constituted by four controllable loads: EV, inverter AC, refrigerator and EWH. In order to simulate their behaviour and energy consumption, the following characteristics were considered.

TABLE I. Controllable Loads Parameters

Parameters	Inverter AC	EWH	Refrigerator	EV
P (kW)	0.22-0.84	2	0.1	0-3.68
C (kWh/°C)	3.2	0.12	0.05	-
R (°C/kW)	6.35	-	107	-
α (kW/°C)	-	0.0012	-	-
BC (kWh)	-	-	-	22
η	3.82	-	3	0.9
θ^w(°C)	-	20	-	-
θ^d(°C)	-	60	-	-
θ^i(°C)	-	20	20	-
v (kW/°C)	-	0.21-0.35[a]	-	-
Initial SOC	-	-	-	0.29

[a] Correspond to hot water consumption values between 3 and 5 l/min

The characteristics of the house and controllable loads influence the evolution of electricity consumption, but there are other aspects that affect their behaviour, such as owners' habits.

Concerning the consumers' habits, the household occupancy, sleeping and bath patterns were considered. The characterization of these patterns is presented in Table II.

TABLE II. Daily Household Behaviour

Patterns	Period (hours)
Occupancy	0-9 and 17-24
Sleeping	23-7
Bath[b]	7-9

[b] Baths periods between 10 and 15 minutes were considered

The relation between the consumers' habits and the active period of the controllable loads is shown in Table III.

TABLE III. ACTIVE PERIOD OF THE CONTROLLABLE LOADS

Controllable loads	Active period (hours)
Inverter AC	24
EWH	24
Refrigerator	24
EV	During occupancy period

B. Comfort Levels Adopted

The regular operation of the TCL implies the adoption of comfort levels predefined by the consumer. The levels of comfort are defined by the temperature set points presented in Table IV.

TABLE IV. LEVELS OF THERMAL COMFORT

TCL	Temperature set point (°C)	Dead band (°C)
Inverter AC	20	-
EWH	60	0.5
Refrigerator	5	0.5

In order to allow the DSO/Aggregator to perform demand actions, the costumer defines intervals of thermal comfort for the TCL (Table V). These thermal intervals are used to define the flexibility of the TCL.

TABLE V. INTERVALS OF THERMAL COMFORT

TCL	Minimum temperature (°C)	Maximum temperature (°C)
Inverter AC	18	22
EWH	55	70
Refrigerator	3	7

Regarding the EV, it was assumed that the owners require the battery fully charged at the time of disconnection.

VII. RESULTS

In this section an evaluation of the potential of the household to participate in DR programs, as well as the analysis of the impact of demand control actions on the behaviour of the controllable loads is made.

Two situations are analysed: the behaviour of the household as a whole and the performance of each controllable load. In the simulation performed, a time step of 5 min was considered.

A. Household

The flexibility of the household is calculated by the HEM at each time step, taking into account the intervals of comfort predefined by the user and the technical restrictions of the controllable loads. The evolution of the flexibility interval (interval between the upper and lower green lines) and the global consumption of the controllable loads (blue line) are shown in Fig. 3. Two periods (2-3 and 19-20 hours) can be identified, where the DSO/Aggregator performs demand control actions by sending power set points to the HEM (red line). In the first period (2-3 hours), the DSO/Aggregator sends power set points to the household, in order to increase the consumption of the controllable loads until reaching the maximum power possible. In the second period (19-20 hours), the DSO/Aggregator reduces the consumption of the controllable loads until reaching the minimum power possible.

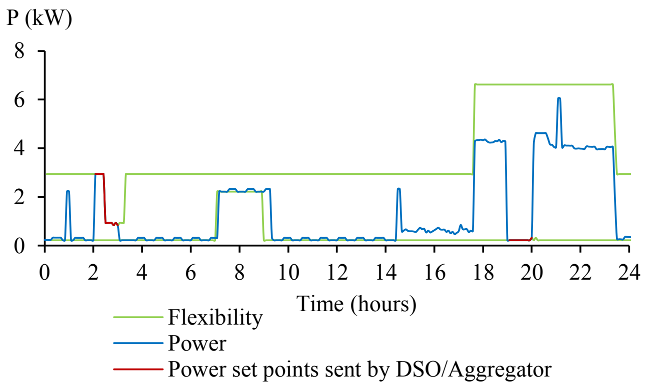

Fig. 3. Evolution of the energy consumed by the controllable loads (blue) and their flexibility

The household flexibility varies over time and depends on the availability of the controllable loads. The flexibility of each load is strongly correlated with their technical restrictions and the interval of comfort predefined by the customer.

B. Controllable Loads

In the periods 2-3 and 19-20 hours, the DSO/Aggregator sends power set points to define the total consumption of the controllable loads. Based on this information, the HEM defines the power of each controllable load (DR operation). In the remaining periods, the household behaves regularly, without any control actions by the HEM. The evolution of the EWH and refrigerator are presented in Fig. 4 and Fig. 5, respectively.

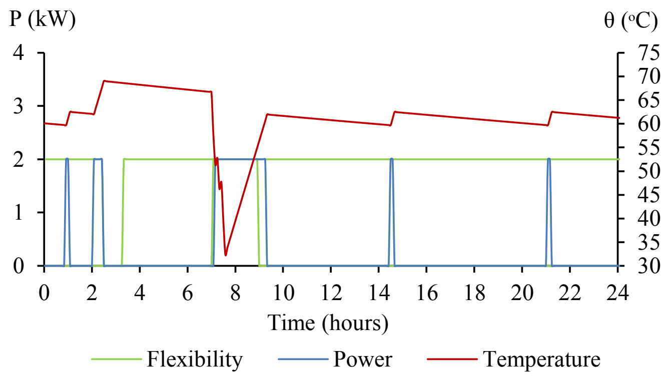

Fig. 4. Evolution of the EWH

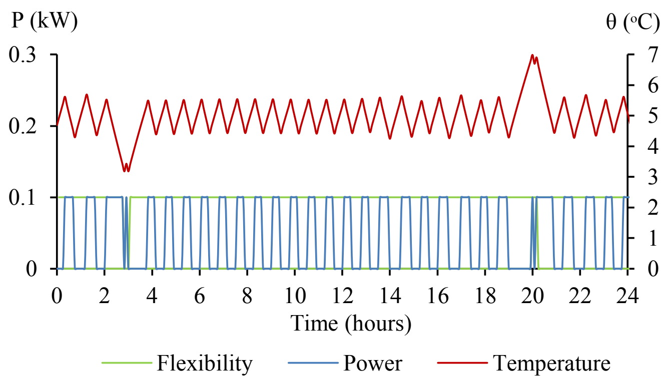

Fig. 5. Evolution of the refrigerator

In regular operation, the evolution of the TCL is essentially conditioned by the temperature set-points (Table IV) and their technical restrictions. In DR operation, the behaviour of the TCL is conditioned by the intervals of thermal comfort (Table V) and their technical restrictions.

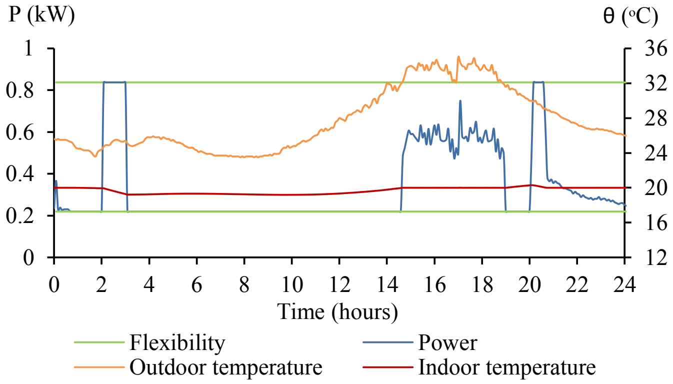

Fig. 6. Evolution of the Inverter AC

The evolution of the EV charging is dependent of the time of connection and disconnection to the grid. In regular operation, the EV charging rate is always 3.68 kW, while in DR operation, the EV charging rate can vary between 0 and 3.68 kW.

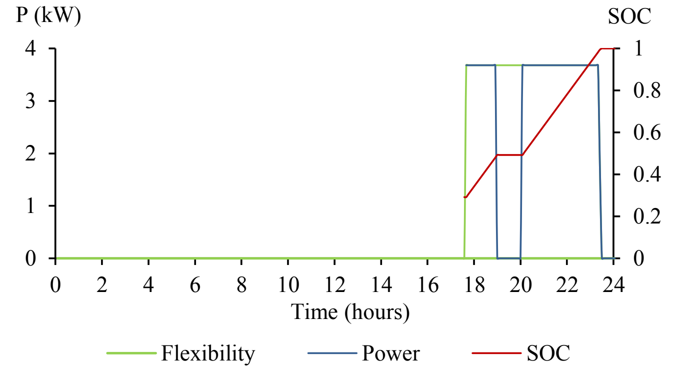

Fig. 7. Evolution of the EV

In DR operation, the four controllable loads evolve within their limits of flexibility, as shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7.

VIII. Conclusion

This paper presented a new method to characterize the availability of household loads to participate in DR. This availability can be used by the Aggregator/DSO to reduce electricity costs and help maintain the balance between demand and supply, contributing to make electric power systems more reliable and efficient. The proposed method calculates the flexibility of the households taking into account information in quasi-real-time, such as outdoor temperatures, consumption habits and comfort patterns related with the controllable loads. A management algorithm to perform demand actions in quasi-real-time, according to the flexibility of the households and DSO/Aggregators objectives was developed.

A case study with a single household was used to evaluate the methodology and algorithm proposed. By analysing the results obtained from the simulations, it may be concluded that the management algorithm can be used to perform demand control actions according to the flexibility of each customer. Yet, to assess the added value of this approach to the operation of electric power systems, simulations for scenarios with a higher number of consumers should be performed.

Other issues, such as the way how the DR can be used to reduce electricity costs and solve technical problems in the electricity networks remain open and should be addressed in future work.

IX. Ackonowledgment

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