Demand Response Model for Hardware Implementation

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***Abstract*—Demand response actions allow to support an adequate domestic load management, considering consumer preferences. In order to develop a hardware tool based on Arduino used to support consumers load management and decisions, an optimization mathematical model is developed and detailed in this paper. In the developed mathematical model, household appliances and electric vehicle are considered as controllable loads. The existence of a storage system based on batteries is considered as well as energy provided by the power grid and solar panel self-generation. The model is implemented using optimization software GAMS (General Algebraic Modeling System) as a Mixed Integer Programming (MIP) problem, where its outputs are used as inputs applied to the hardware used as interface between the optimization mathematical model and controllable loads.**

Keywords— Demand response, Load management, Mixed Integer Programming,

I. Introduction

Demand response (DR) is used as a mean of consumption peak reduction promoting energy efficiency [1]. Peak reduction contributes to minimize investment in production centers and in transmission lines allowing to use stored energy when consumption increases occur. Energy efficiency, in its turn, intends to mitigate energy losses in the transmission lines and promote consumption pattern changes accordingly with the local renewable generation availability. These measures have environmental impact and contribute for the urgent needed climate changes measures, by using renewable energies, deferring new pollutants power plants installation [2] and decongesting power networks. To accomplish this impact, domestic load management is useful to achieve peak consumption reductions, to efficiently shift loads, contributing to the load diagram flattening [3]. It is also intended that by performing domestic load management, consumers are able to reduce their energy bill, through the domestic loads' consumption allocation in those time periods where the energy price is lower [4]. However, it really matters to develop algorithms that allow consumers to keep load management autonomy, guaranteeing and enhancing their wellbeing. In addition, the existence of an adequate interface tool between the mathematical algorithm, controllable loads (CL) and the consumer itself, is preponderant to domestic consumers' inclusion into load management and to consolidate consumers as active stakeholders in the power grid management [5].

Different criteria is used to classify DR programs, mainly because these programs are developed to provide answers to specific scenarios, however some convergence can be found in literature around two major types: time-based-programs (TBP), also known as price-based-programs (PBP) [6,7] and incentive-based-programs (IBP) [8]. When DR is price-based, consumers are more subject to price fluctuations and load control decisions are more limited [9]. When DR is incentive based, the load control is performed accordingly with power grid events, i.e, for example, when more congestion is verified, the utility can drive consumers to a more adequate consumption profile, through a load shifting action [10]. In [11], TBP encompasses time-of-use, real time pricing and critical peak pricing programs. On the other hand, IBP encompasses direct load control, interruptible service, demand bidding, emergency demand response, capacity market and ancillary service market.

Despite the increasing number of DR programs in the last decade, such as the ones referred in [12] and also mentioned in [13], in this paper the addressed DR model can be classified as TBP, because domestic consumers are able to change consumption patterns driven by the energy price. In this case, price is the trigger that leaded to the DR model development proposed in this paper. The energy price mainly derives from the utility policies, the wholesale market, self-generation systems and energy storage systems. However, for domestic consumer´s load management it is directly related with energy prices,

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therefore the existence of self-generation and storage system increases the load management options regarding the intended energy bill reduction, or environmental concerns.

The addressed DR model is developed with the purpose of providing a tool that gives support to domestic consumers decisions regarding CL management, without the need of a deep technological knowledge, allowing the inclusion of a hardware interface between this DR model and the domestic load appliances chosen as CL. To accomplish this domestic consumers' supporting tool, dedicated hardware will be designed and assembled to act as a load management interface. Initial system configuration and setup is done using an EXCEL spreadsheet that generates a set of configuration text files, which are then transferred to the interface load management hardware via a standard micro SD card. The interface load management hardware will consist of an ATMEL ATMEGA 328P microcontroller, running at 16MHz; a Real Time Clock based on the DS3231 from Maxim Integrated with battery backup; an USB to serial interface based on the FT232R from FTDI Chip and 6 output relays (SPDT) one for each considered CL. This low cost prototype, of approximately 50€, can be easily installed contributing for a wider domestic load management systems implementation. The system formed by the DR model, interface hardware and the domestic loads defined as CL is designed having into account a simple and economic solution, when compared with the ones already available in the market.

This paper is organized as follows: in section II load management model is addressed, characterizing the considered CL, storage and self-generation system; in section III two case studies are analysed considering the storage system influence into the load management model. Finally, in section IV some conclusions about the developed work are discussed.

II. Load Management Model

In this paper the optimization mathematical model is based on [6] and is developed considering 6 domestic CL, detailed in Table 1. For the optimization algorithm, CL are characterized by their rated power, operation time and working time scheduling defined by a starting and ending time. The operation time corresponds to appliances' working time, while the working time scheduling refers to the defined time period where the appliances are allowed to work. Both operation time and working time scheduling are defined by the consumer.

TABLE I. DOMESTIC CL OPERATION CHARACTERISTICS

Controllable loads	Power (kW)	Operation time (h)	Starting time (h)	Ending time (h)
Oven	2.4	0.5	15:00	19:00
Water heater	2.0	3	03:00	07:00
Washing machine	2.4	2	00:00	07:00
Drying machine	2.0	1	00:00	07:00
Dish washer	2.0	2	17:00	21:00
EV charger	4.6	7	00:00	09:00

For the domestic load management model it is considered 10.35 kW of contracted power and a tariff that settles lower energy prices between 22:00 and 08:00, 10.09 c€/kWh, corresponding to off-peak hours and higher energy prices for all the other hours, 19.48 c€/kWh, corresponding to peak hours. Also, it is considered a 2 kWh Li-ion batteries storage system with a charge/discharge cycle efficiency of 81%, and the existence of self-generation given by 1.5kW of PV solar panel installed power. The total daily power generation from the solar panel is 7.73 kWh. The excess generation can be sold to the grid at a price of 4.72 c€/kWh. There is a base consumption that is given by non-controllable loads (NCL) consumption power, such as lights, refrigerator and computer, for example. The total daily consumption of the CL and NCL is 66.91 kWh.

The optimization model considers consumer's net revenue maximization, i.e., the maximization of the difference between the revenue obtained from selling the excess generation to the grid and buying electricity costs, subject to a set of constraints. The mathematical formulation of the developed model is given by (1-16), where the variables and explanation of each equation are given at the end of the addressed mathematical formulation.

$$\underset{Pv_t, Pc_t}{Max}\ L = \sum_{t=1}^{T}(\lambda v_t \cdot Pv_t - \lambda c_t \cdot Pc_t) \quad (1)$$

s.t.

$$Pc_t + Pdch_t + Pg_t = Pv_t + Pch_t + Pcl_t + Pncl_t \quad (2)$$

$$Pcl_t = \sum_{j=1}^{J}\left(P_j \cdot u_{j,t}\right) \quad (3)$$

$$0 \leq Pc_t \leq Pcont \cdot uc_t \quad (4)$$

$$0 \leq Pv_t \leq Pcont \cdot uv_t \quad (5)$$

$$0 \leq Pch_t \leq Pch^{max} \cdot uch_t \quad (6)$$

$$0 \leq Pdch_t \leq Pdch^{max} \cdot udch_t \quad (7)$$

$$\sum_{t=1}^{T} u_{j,t} = 4r_j \quad (8)$$

$$\sum_{t=k}^{k+4r_j-1} u_{j,t} \geq 4r_j\left(u_{j,k} - u_{j,k-1}\right) \quad (9)$$

$$u_{j,t} = 0,\ t > 4f_j\ and\ t < 4s_j \quad (10)$$

$$u_{'Washing\ machine',t} + u_{'Drying\ machine',t} \le 1 \quad (11)$$

$$uc_t + uv_t \le 1 \quad (12)$$

$$uch_t + udch_t \le 1 \quad (13)$$

$$W_t = W_{t-1} + Pch_t \cdot \eta ch - \frac{Pdch_t}{\eta dch} \quad (14)$$

$$W^{min} \le W_t \le W^{max} \quad (15)$$

$$W_{t=0} = W_{t=T} \quad (16)$$

Where, (1) represents the consumer's net revenue, L, obtained for the simulation period T, where λv_t and λc_t are the energy selling and buying price, respectively; Pv_t and Pc_t are the power sold and bought from the grid, respectively, all of them considered at a time instant t, that in this paper is set to a 15-minute time period.

Equation (2) is the balance equation, where $Pdch_t$ is batteries' discharged power, Pg_t is the power produced by the PV solar panel, Pch_t is the batteries' charged power, and Pcl_t and $Pncl_t$ are the CL and NCL power consumption, respectively.

The power consumption of CL that are working is given by (3), where P_j is the power consumption of controllable load j and $u_{j,t}$ is a binary variable that is equal to 0/1 if controllable load j is off/on.

The set of equations 4 to 7 refers to the limits of the buying and selling power, and with the limits of batteries' charging and discharging power, respectively. In these equations, $Pcont$ is the contracted power, Pch^{max} and $Pdch^{max}$ are the batteries maximum charge and discharge powers. uc_t, uv_t, uch_t and $udch_t$ are binary variables equal to 1 when the consumer is buying power from the grid, selling power to the grid, the battery is charging, and the battery is discharging (in this order). Otherwise, these values are settled to 0.

Equations 8 to 10 refers to operation (r_j), starting (s_j) and ending (f_j) times of the controllable load j.

Equation (11) prevents the washing and the dryer machines from working simultaneously.

Equations (12) and (13) prevent the simultaneity of buying and selling power, and of charging and discharging batteries, respectively.

Finally, equations 14 to 16 are related with the batteries' energy storage. Equation (14) accounts for the energy stored in each instant t, W_t, where ηch and ηdch are the batteries charging and discharging efficiencies, respectively. Equation (15) sets the batteries energy stored limits between a minimum (W^{min}) and a maximum (W^{max}) value. Equation (16) assures that batteries' energy storage has the same value at the beginning and at the end of simulation period.

III. CASE STUDIES ANALYSIS AND DISCUSSION

For the load management model addressed in section II, two different case studies were considered regarding the existence or not of a battery storage system and its impact into the CL distribution along a 24h period. This period was chosen because, as referred in section II, there are different energy prices during 24h. Lower energy prices are settled between 22:00 and 08:00, during week days and weekends, and for that reason is considered that consumption pattern remains constant during the week. This means that the most relevant loads, i.e., the ones with higher energy consumption values such as the washing machine, for example, show similar consumption pattern during the week.

A. Case study with storage system

Considering the existence of the storage system described in section II, the mathematical model outputs are shown in Fig. 1 to Fig. 3.

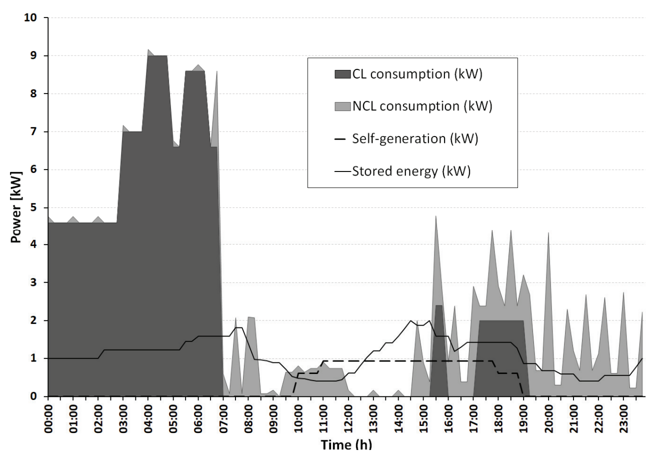

Fig. 1. Power consumption, self-generation and stored energy distribution.

In Fig. 1, the load diagram outline for CL and NCL, including self-generation and the system stored energy can be observed. The founded relation between sold and bought power in order to supply the overall consumption needs are shown in Fig. 2, and the resulting CL distribution can be observed in Fig. 3, where the on/off working status is given by the binary variable, as considered in section II .

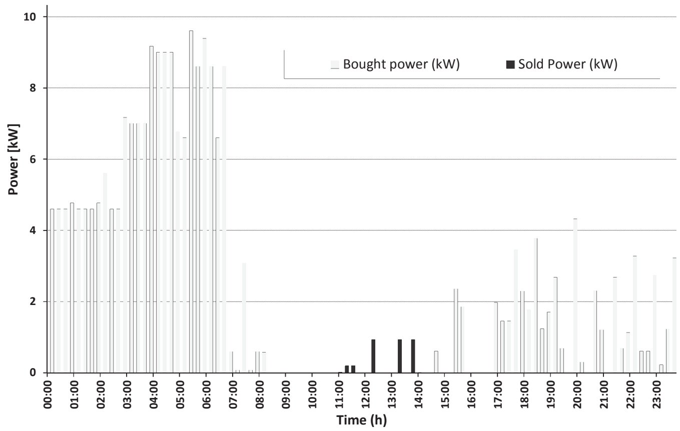

Fig. 2. Relation between bought and sold power considering energy storage system.

From Fig. 1 and Fig. 2, it can be observed that CL are working within the time periods defined in table 1 and that bought energy is used to accomplish consumption needs and to store energy. This is mainly noticeable between 00:00 and 07:00, where the CL are working. Self-generation is used to fulfill NCL consumption needs and to increase consumers profit by selling the remaining energy to the power grid. In addition, is also used to charge the batteries, when no NCL consumption is verified, avoiding buying energy during peak periods. Stored energy management is optimized regarding not only CL and NCL consumption, but mainly considering energy bought and selling prices, where the corresponding bought and sold energy is addressed in Fig. 2. In Fig. 3 can be observed the simultaneous work of several CL, which naturally contributes for the power consumption highest values observed between 00:00 and 07:00, however these values are inferior to the considered contracted power, as expected.

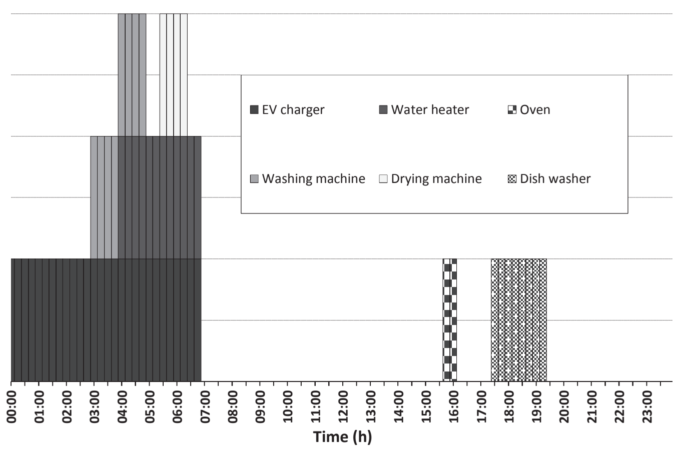

Fig. 3. Controllable loads working status and distribution.

B. Case study without storage system

Considering the inexistence of storage system, the corresponding optimization mathematical outputs with the adequate simplifications are shown in Fig. 4 to Fig.6.

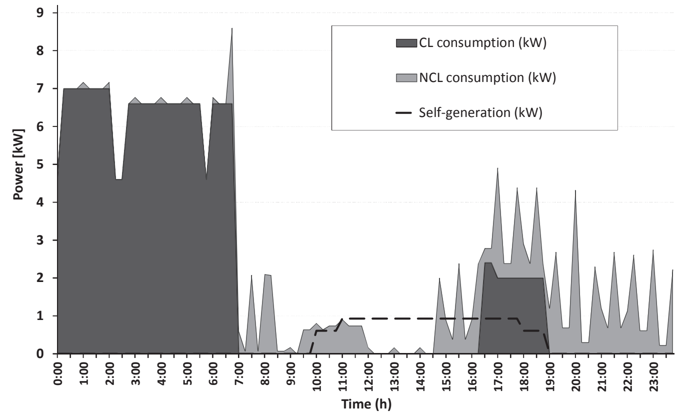

Fig. 4. Power consumption and self-gneration distribution.

In Fig. 4, it can be observed that power consumption peak is reduced in order to minimize bought power, as shown between 00:00 and 07:00, in Fig. 5. This means that CL distribution is performed in order to assign CL consumption mainly during off-peak hours and also in time periods where is possible to take advantage of self-generation. In this case study, self-generation is mainly used to assure consumption demand, as shown in Fig. 5 (between 11:00 and 14:00), rather than being also used for energy storage, as observed in the previous analyzed case study.

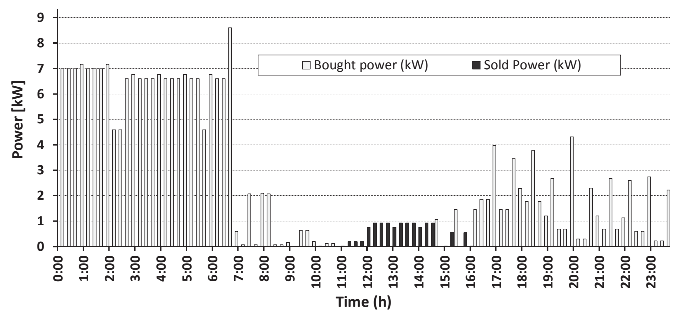

Fig. 5. Relation between bought and sold power.

The corresponding CL distribution is shown in Fig. 6, where the on/off working status is given by the binary variable, as considered in section II.

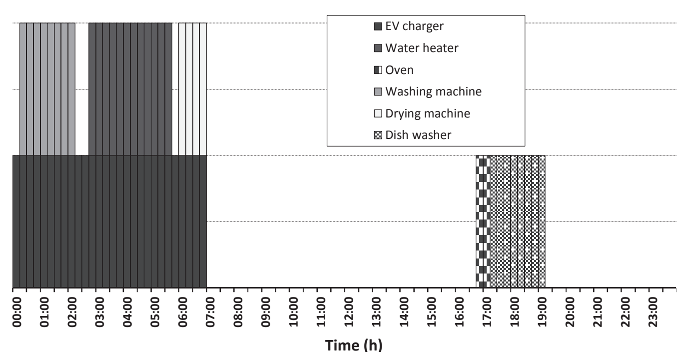

Fig. 6. Controllable loads working status and distribution.

C. Case study overall comparison

Considering CL and NCL consumption, self-generation, sold and bought power, and considering the existence of a storage system, the results can be observed in Fig. 7.

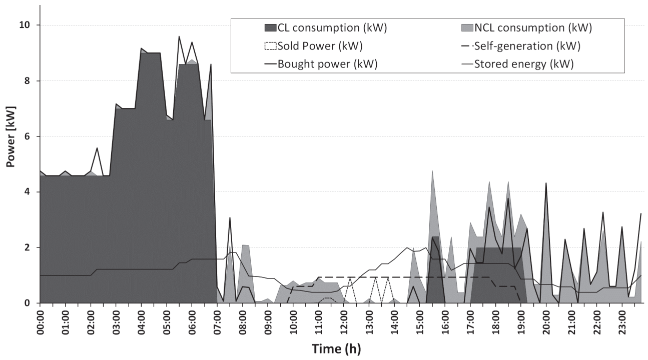

Fig. 7. Power consumption, self-geration, stored energy, bought and sold power distribution.

For the same considerations, but without the existence of a storage system, results can be observed in Fig. 8.

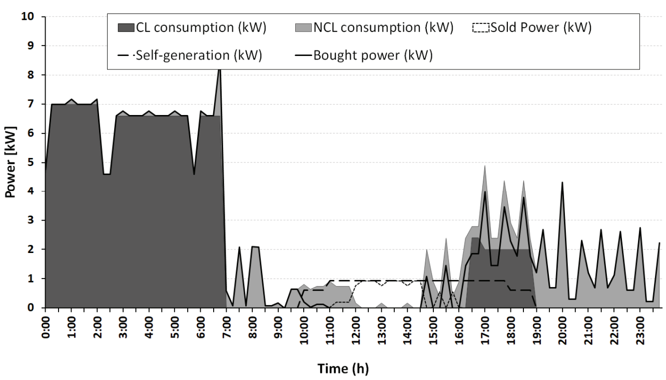

Fig. 8. Power consumption, self-geration, bought and sold power distribution.

Observing Fig. 7 and Fig. 8, it can be noticed that sold power is more significant in the absence of a storage system. In fact, without the storage system the energy sold during the day is 2.86 kWh, while with the storage system it is 0.78 kWh, meaning that it is preferable to store energy to be used afterwards during peak hours when the energy bought is more expensive, rather than sell it to the power grid. Also, it can be observed in Fig. 8 that bought power is only used to fulfill load demand, as expected. However, the energy bought from the grid is higher without the storage system (62.01 kW) than with the storage system (60.67 kWh), since the consumer can not use the stored energy in peak hours. The load management system including the storage system allows the consumer to decrease its energy bill approximately 9.4 € in one month.

IV. Conclusions

The developed work showed an optimization mathematical model that allowed to perform CL management. The CL operation time frame and predefined working periods are defined by the consumer. This model was implemented using GAMS software, and the obtained results showed a consumers' net revenue maximization, with the allocated CL in those defined time periods. In addition, results showed that consumption power is always below the contracted power limit. From this work, it is also possible to infer that the addition of a storage system supporting self-generation contributes for energy bill reduction, where the increment of self-generation energy is preponderant for achieving even better results. The mathematical model outputs are adequate being applied directly into a low-cost hardware interface tool prototype that will be implemented in a near future, showing that it is possible to widen CL management concept because it is possible to gather larger domestic consumers groups.

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