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Appliance Shifting for Sequential Processes in Home Management System

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Abstract

Home management systems are evolving to enable a more adaptive model to the many consumer's behaviors, such as, periods of more consumption, habits of appliance use, amongst others. In another perspective, there are processes that require a start-after and sequential operation of multiple appliances, which currently is not a feature that exists in many of the home management systems. The present paper proposes a model to formulate sequential appliances load shifting, such that, the respective processes that the consumer has are maintained implemented correctly. The case study considers multiple appliances that exist in a home, with a sampling of 15 minutes, which is important in order to better observe the appliances consumption cycles.

Keywords: demand response, load shiting, home energy management system, smart grid

1. Introduction

Home energy management systems are on the raise since the green and sustainable mentality has become a trend in the present consumers and power systems [1]. The need for these systems is related with the implementation of demand flexibility providers and on-site generators in a new stage of power systems operation, focused in the smart grids implementation. Home energy management systems gain a new relevance in the context of power systems, since the majority of consumers is residential, and thus a high potential of efficiency can still be uncovered by these systems [2]–[5]. The architecture of a home energy management system depends upon the available resources and the functionalities that can be adopted. In [6], it is presented a table that clarifies the possible functionalities of home energy management systems - Table **1**.

Demand Response (DR) is characterized by the modification of the consumer's typical consumption profile, in response to price signals or monetary incentives [7], [8]. This concept is a major pillar of smart grids implementation, since it allows for flexibility provision which grants more robustness to power systems. DR can be integrated in energy management systems, per example, control over given appliances or loads that can be optimized either by unnecessary consumption reduction or wise choice of consumption times [9]–[11]. In the consumer's perspective, energy management systems can bring several adaptive features that increase the consumer's comfort, and also reduce the energy expenditure of the consumer's operation with an efficient strategy [12], [13]. From an upper level, such as system operators, the energy systems of the consumers allow for an easier control related with the implementation of DR [14].

Table 1. Possible functionalities assumed by the home energy management system.

Modules	Service Description
Monitoring	Real-time information about the present operating conditions of the system, allow for a more reasoning by the consumer and energy saving potential
Logging	Historical data storage allows for a deeper analysis of the consumption profile and the main sectors that can be improved through demand response
Control	Direct and remote control of loads
Management	Management of several resources, as demand response strategies, on-site generators, plug-in electrical vehicles, and energy storage
Alarm	Fault detection and notice is also an important part of a management system

In the demand response environment, load shifting is a program that provides a useful management of both consumption and generation [15]. In what concerns consumption, load shifting allows for the transfer of load from less to more attractive periods (e.g. lower energy tariffs when dynamic pricing is considered) [16], [17]. Regarding generation, and from an operator's point of view, load shifting is important to transfer load from periods where the generation availability is lacking to others when it is abundant (e.g. photovoltaic energy is only available during the day). Also, the load shifting approach insures that the removed load is reallocated to another time, and therefore the consumer's consumption is respected. The implementation of DR programs is often associated with management systems which suggest optimized operation scheduling using these DR strategies.

The inclusion of home management systems is related with multi-agent systems, such that each agent is characterized by being an autonomous and distributed entity, that can be intelligent (in this case yes, since the consumer is an active part of the energy management system) or not, and which are capable of interacting with other agents building up a bigger system and bidirectional communication [18]. In this way, the smart grid implementation implies multi-agent systems that offer several features of sustainability and robustness, moreover, promotes an agent network interaction amongst its several components considering a mutual goal, the power system adequate and secure operation [19], [20].

2. Home Energy Management System

The objective function considered for the energy management system is showed by equation (1), that considers the minimization of the energy bought, $P_{(s,t)}^{Sup}$, from the main network. The energy tariff from the main network is dynamic changing hourly over time, $C_{(s,t)}^{Sup}$, and in this way there is the need to adjust the energy amounts in each period, since it is considered over a sampling time of 15 minutes, thus, $\Delta t = 4$ since one hour is composed of 4 periods of 15 minutes. In equation (2), it is presented the power balance of the home that considers the energy bought from the main network, the load shifting, $P_{(a,t,d)}^{Shift}$, and load reduction, $P_{(a,t,t)}^{Shift}$, in each period. The load curtailment program considers only the appliances that are not participating in the load shifting, and the loads that are in the load shifting program are not participating in the load curtailment program.

The dependency vector (*D*), with length equal to the total number of appliances, that the consumer uses to declare the mandatory sequential operation of an appliance or appliances. This is made by assigning a non-zero integer number to the appliances which are sequential, where different sequences must have distinct integer numbers. In this way, the consumption verified by sequential appliances is summed and considered as a single load to the scheduling optimization, therefore, the modelling is made easier by considering a single given process that implies several appliances. Also, when considering sequential operation of a given appliance, an integer number is also assigned in the dependency vector, and being a single load, is equally modelled as the sequential appliance.

$$\min OC = \sum_{s=1}^{S} P_{(s,t)}^{Sup} \cdot C_{(s,t)}^{Sup} \cdot \frac{1}{\Delta t} \tag{1}$$

$$\sum_{s=1}^{S} P^{Sup}_{(s,t)} = \sum_{a\in D=0}^{A} P^{Load}_{(a,t)} + \sum_{a\in D>0}^{A} P^{Load}_{(a,t)} - \sum_{d=1}^{T}\left[P^{Shift}_{(a,t,d)} - P^{Shift}_{(a,d,t)}\right]$$
$$\forall t \in \{1,...,T\}, D=\left[a_1, a_2, (...), a_n\right] \tag{2}$$

The energy contract that the consumer has with the main network limits the energy use in certain amount (e.g. this is often performed by a circuit breaker at the connection before the installation). This is formulated according to equation (3) that imposes limits to the energy bought from the main network.

The load shifting demand response program considers that a given load can be transferred from or to another period, being this decided according to the energy consumption cost in each of the periods considered. In this way, $P^{Shift}_{(a,t,d)}$ is a 3D matrix where in the first dimension, *a*, represents a given appliance, and in the second and third dimension, *t* and *d* represent a given period. In this paper it is considered that $P^{Shift}_{(a,t,d)}$ represents the energy transferred from period *t* to any other period *d*, thus, the sum along the third dimension reflects all the energy that has been transferred from period *t*, while the sum along the second dimension reflects all the energy transferred into period *t*. The load shifting limits are represented by equation (4) and these in this case are defined by the consumer which is the owner of the installation and the appliances that compose it. In order to perform sequential appliance or operation shifting, equations (5), it is used decision binary variables that provide the necessary conditions to implement these processes.

$$P^{SupMin}_{(s,t)} \le P^{Sup}_{(s,t)} \le P^{SupMax}_{(s,t)}, \forall s \in \{1,...,S\}, \forall t \in \{1,...,T\} \tag{3}$$

$$P^{ShiftMin}_{(a,t,d)} \le P^{Shift}_{(a,t,d)} \le P^{ShiftMax}_{(a,t,d)}, \forall a \in \{1,...,A\}, \forall t,d \in \{1,...,T\} \tag{4}$$

$$P^{Shift}_{(a,t,d)} = \begin{cases} P^{Load}_{(a,t)} \cdot \lambda^{Shift}_{(a,t,d)}, t \ne d \\ P^{Load}_{(a,t)} \cdot \lambda^{Shift}_{(a,t-1,d-1)}, t \ne d \wedge t,d > 1 \end{cases}$$
$$\forall a \in \{1,...,A\} \wedge a \in D > 0, \forall t,d \in \{1,...,T\} \tag{5}$$

In this section, it was approached the mathematical formulation of the optimization problem regarding the implementation of consumer's flexibility. The consumer can obtain its consumption scheduling such that its operation costs are minimized, considering the energy tariff at different periods of the energy supplied from the main network, and considering load shifting that respects the consumer's preferences of operation.

3. Case Study of Sequential Scheduling

In the present section, the case study approaches a sequential scheduling of appliances namely, a washing and drying machines sequential operation, and an individual operation of a cooker. In Fig. 1, it is presented the scheme of the proposed methodology and also the context of the applied case study.

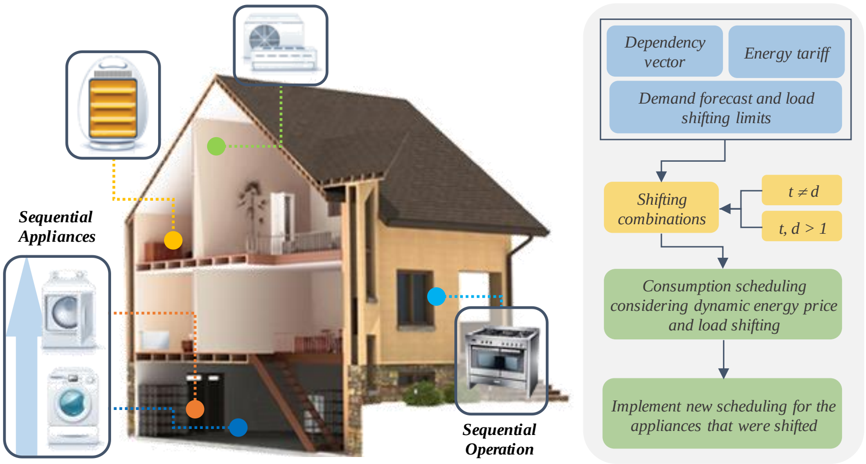

Fig. 1: Overall scheme of the proposed methodology.

The case study involves twelve appliances: television, fan, fridge, computer, electric heating, oven, drying machine, washing machine, microwave, toaster, sockets, and cooker (this is the order considered in the *D* vector of dependency), however, only three of these are considered for load shifting (washing, drying machine, and cooker). The drying machine follows up the activity of the washing machine (sequential appliance), and the cooker must be respected due to the comfort and process restraints that it involves (sequential operation). The following Fig. 2 shows the consumption forecast for each of the appliances considered.

By Fig. 2 it is possible to see that the peak consumption occurs at 00:15, with an amount of 2.1 kWh/Δt, and the major contributor for this amount is the consumption from sockets. The data presented from Fig. 2 is adapted from [21]. The data concerns a single household located in the Netherlands, that is monitored regarding four sets: electricity monitoring, ambient, occupancy, and household information. The level of data available allows for a wider consideration of consumer comfort preferences that may influence and provide more interest in the demand response programs implementation.

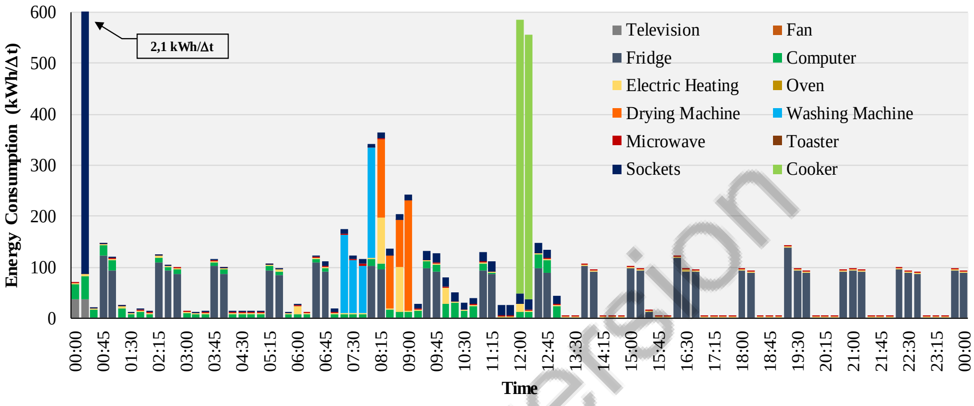

Fig. 2: Consumption forecast discriminated by appliance.

The energy price considered is dynamic over time, thus inducing the consumer to be more aware of its consumption in given periods. In this way, the following Fig. 3 shows the energy tariff considered from the main network. The green area in the graph shows the time table that is more advantageous for the consumer to apply load, since is where the lowest energy tariff is located. In equation (6), it is showed the considered vector of dependency.

$$D = \left[0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 1,\ 1,\ 0,\ 0,\ 0,\ 2\right] \qquad (6)$$

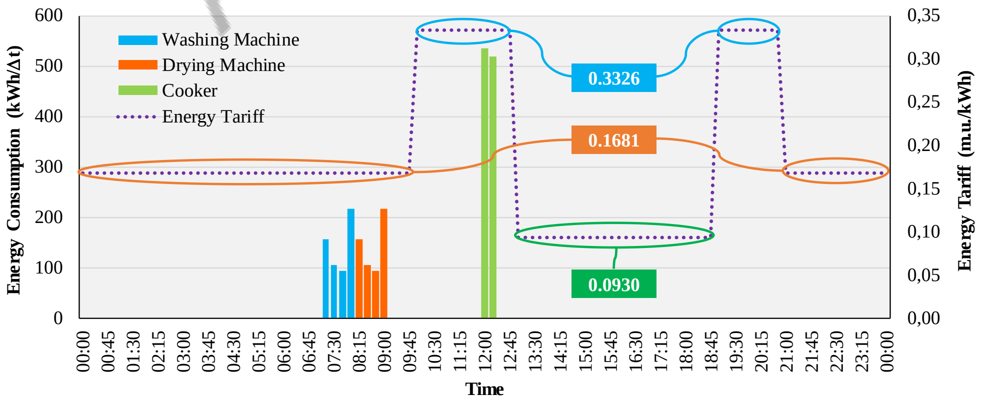

Fig. 3: Energy tariff along the given periods and consumption forecast of the shifting loads.

4. Results

The present section shows the results obtained in terms of scheduling of the appliances defined by the dependency vector and the energy bought from the network. In Fig. 4 it is shown the total scheduling of the consumer's consumption, presenting the energy bought from the supplier, the initial demand before flexibility arrangement, and the final demand after flexibility implementation. Demand is divided into two categories, namely, fixed and dynamic, where the first represents the appliances that cannot be shifted, and the latter to the appliances that can be shifted to other periods. In this way there is a fixed cost for the consumer because of the fixed appliances, however, with dynamic appliances the energy management system adjusts their implementation to reduce the cost of it.

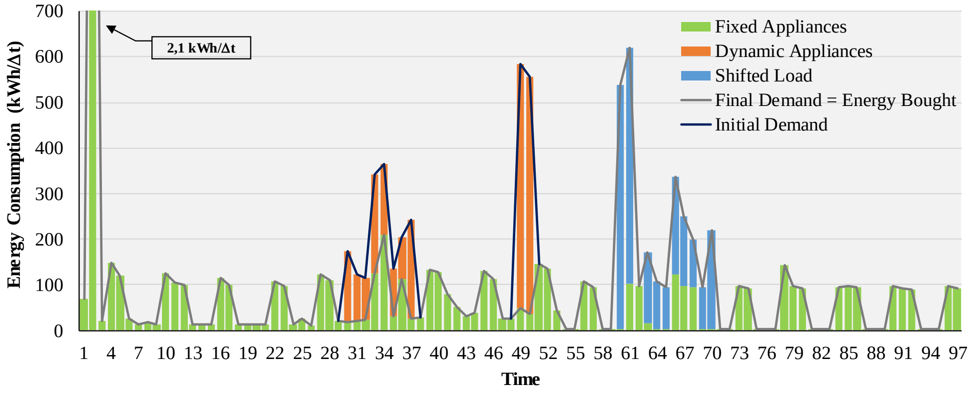

Fig. 4: Energy schedule obtained from the optimization with changes in consumption.

In Fig. 5 is shown in more detail the load shifting amounts and periods where were applied the dynamic appliances. As one can see, the operation of the drying machine follows the operation of the washing machine, sequentially, and these are shifted as so, demonstrated by the below figure. In the case of the cooker, this is not related to any other appliance, however, its operation must be respected since is normally associated to a process that requires a certain level of consumption that cannot be interrupted. In this way, the proposed methodology insures that these appliances operation and processes are respected during their scheduling minimizing the impact on the consumer's comfort and preferences.

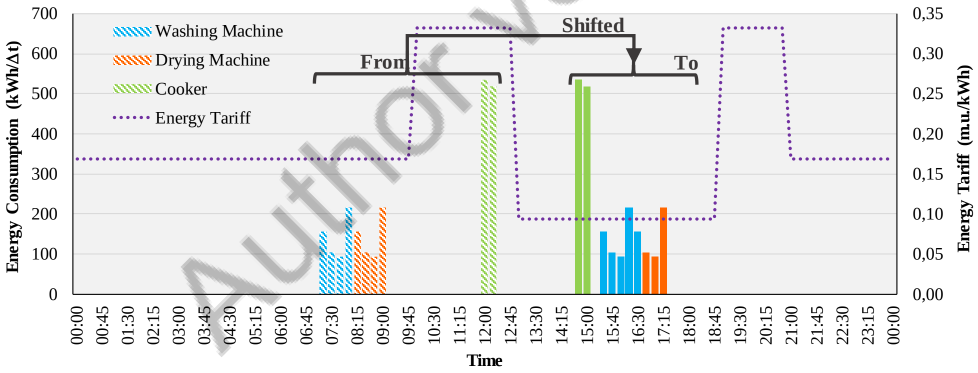

Fig. 5: Initial consumption forecast and load shifting obtained from the optimization.

The example given by this case study is related to residential consumer's operation, however, this methodology is equally useful or more in a commercial and industrial context. Specially in industrial context, the sequential operation of individual appliances or processes becomes more relevant, since normally these are needed to obtain a final product or results.

5. Conclusions

The increasing number of appliances in every type of consumers, brings several modifications in the consumption profile, and changes the operation costs of the consumers. Moreover, the need for efficiency in power systems is nowadays more important than ever, with a raising sustainability and green energy trend. In this way, the present methodology proposes a scheduling optimization of the consumer's consumption, discriminating individual appliances contribution to the total load. The scheduling considers sequential load shifting of certain appliances together with dynamic tariffs offered by the supplier (main network), in order to minimize the operation costs of the consumer. In this way, the algorithm searches for the least costly periods to shift consumption into, being it from periods where a higher cost is at play. Future work related to the present paper, involves the consideration of more resources for the scheduling, namely, the modelling of on-site generation and with growing importance of the industrial context, since this environment presents itself as the one with more to gain from sequential load shifting. Also, the inclusion of more demand response programs is interesting to analyse, in order to observe the influence that these may have on the load shifting, considering other relevant data associated with the consumer operation (e.g. occupancy).

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