SIMPLIFICATION AND EVALUATION OF DEMAND RESPONSE BY THE USE OF STATISTICAL AGGREGATED MODELS

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ABSTRACT

The participation of Demand Response in energy and operation markets is gaining interest in the last years due to the necessity of integrating renewable resources in the Power Systems. The potential of small demand segments is very high, but its complexity (thousands of customers to achieve the same potential that large customers) and costs (for instance, measurement and communication requirements) arise as important barriers for DR. These barriers are to be analyzed in detail, especially for Ancillary Services. Likewise, this paper presents the basis of a load modelling methodology (elemental and aggregate ones, PBLM) for different electricity markets which demonstrates through simulations the capabilities of the tool for the engagement of these segments on DR. These simulations can help to overcome some of the main barriers and facilitate the deployment of DR.

INTRODUCTION

Ancillary Services (AS) are increasingly provided by Demand Response (DR) in several markets worldwide (reaching in some cases as much as 15%) and the trend is growing [1]. These markets favor the participation of DR although there are still a few strict restrictions. There does not appear to be any implicit or insurmountable barriers to load providing any of AS, if the same capabilities that supply resources can be demonstrated.
In addition, DR participation is interesting from an economic point of view both for customers and markets. A NREL report [2] states that increasing reserves are expensive and DR can easily cover a hundred hours a year of reserves with savings up to $600M/year in operating costs instead of using conventional and additional reserves. Those represent, according to some estimates [3], between $1 and $5kW/month (capacity) and additionally energy payments if they are activated.
To define a framework for the tools to be developed, some conditions for the different AS have to be analyzed. For example: the main characteristics of the offers (i.e., symmetrical vs. unsymmetrical offers in regulation); the time availability of the resource; the foreseen revenues, or the time delay for response. For example, the operating time of the resource appears as an important issue for loads. The duration of the events curve for PJM system shows that 98% of the events in synchronized reserve last less than 40 minutes and the average time per event is about 11 minutes [2]. Moreover, it can be inferred, from research on market database, that some services (regulation) provide higher incentives than other services (synchronous reserve), whereas requirements of response make more complex the response [2].
This paper aims to demonstrate how DR in small demand segments (residential, commercial) can contribute to provide AS and reduce the need for conventional generation. Moreover, this paper wishes to present aggregators (and other market's actors) some tools to evaluate and define, in an easier way, the bidding and operational parameters to expedite DR in AS markets.

PHYSICALLY BASED LOAD MODELLING

Since DR is complex for the demand side, the philosophy adopted for modelling is to save time, information and resources and, consequently, use the same modelling basis for different DR policies, whenever possible. This seems affordable with the use of PBLM models that represent the processes occurring between load and its service, involving physical information. An additional problem for small customers is aggregation: all these processes require some time, but time is scarce when reacting to AS signals. To gain time without an excessive loss of accuracy in response, both for elemental and aggregated, tools have to be simplified to some extent. Figure 1 presents an example of this kind of models. These usually have several components (sub-models) which use thermal-electrical analogies, for example:
- Dwelling/environment: parameters that represent heat losses (conduction/convection through walls: h_a, a_w; the

floor: a_{rg}; windows, a_g), ventilation losses/gains (H_V); as well as heat gains: solar radiation (H_{sw}, H_w); internal gains due to inhabitants (H_r) or appliances (H_a). Also, the model takes into account heat storage from the specific heat of walls (C_w), indoor mass (C_a) or roof/ground (C_{rg}).

- The appliance: and its energy conversion into heat (space heating), "cold" (air conditioning), or hot water. This is represented by a current source (H_{ch}).
- Control mechanisms (one or several) which decide the demand: a thermostat in some loads, i.e., m(t) in Figure 1.

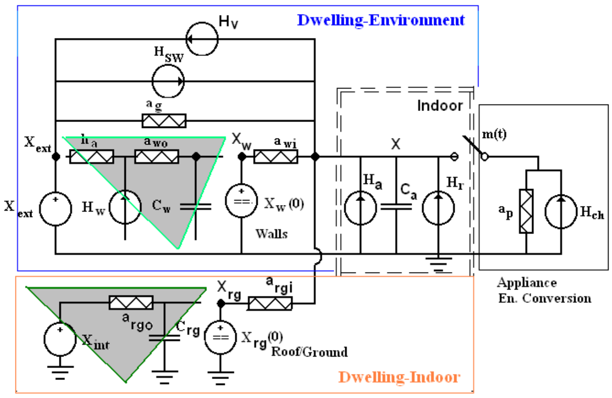

Figure 1. Example of PBLM for a residential dwelling (30m^2)

- The state variables that usually are temperatures: indoor (X), walls (X_w) and roof/ground (X_{rg}).

Model order reduction

Models, such as the one shown in fig. 1, are third or higher order models, if you consider in detail the heat losses, gains or storage in each element (wall, roof, ground of the dwelling), or if the appliance has energy storage (in this case, new capacities C that represent the capacity of storage in bricks, water or other phase-change material, have to be considered). The higher the order of the system, the more complicated is its resolution and the aggregation of these models. This is a problem that does not arise in modeling for thermal design, but appears for DR and Energy Efficiency. For instance, the reduction of an Energy Plus model of a complex dwelling with a RC model (similar to fig. 1) developed with BRMC toolbox [3] is presented in [4]. The boundary condition for this order reduction is to consider thermal masses and the effect of solar radiation (both are neglected in some approaches to DR modeling, see [5]). Our method is based on the time response given by natural frequencies of state-space matrices (see table 1, for three residential dwellings in Spain). It can be seen that the dynamics of $X_w(t)$ (walls) and $X_{rg}(t)$ (ground/roof, corresponding to T_2, T_3 constants) are slower than X(t) behavior.

Table 1. Time Constants of Appliance-Dwelling System Response (T_1, T_2, T_3) and its first order equivalent (T_{eq})

Load	T_1 (h)	T_2 (h)	T_3 (h)	T_{eq} (h)
Load 1	0.95	7.25	14.3	1.15
Load 2	1.15	8.9	12	1.37
Load 3	1.61	17.82	20.83	1.79

This can also be seen in fig 2a. The change of walls temperature in five hours is around 1.5ºC (note that this temperature is uncontrolled whereas X(t) is controlled by thermostat m(t)). For these reason both variables $X_w(t)$, $X_{rg}(t)$, but not heat flows, are replaced with DC sources $X_w(0)$ (walls) and $X_{rg}(0)$ (ground), i.e., values at the beginning, "t=0", of the DR control period (see green triangles in fig 1). This allows the consideration of thermal masses and flows in some way. Figure 2a&b show the appliance state (ON/OFF) and the temperatures for the original (3rd order) and simplified (1st order) models, when a control action is applied from t=14h to 16h30. It can be seen that X(t) changes faster than $X_w(t)$. Also, errors in the state of the load and temperature are important. On the contrary, for another DR action from t=14 to 14h45m, m(t) and X(t) approach 3rd order model dynamic. In conclusion, for typical AS times the reduced model represents with an acceptable accuracy the load behavior (note that T_{eq} is in the range of AS requirements which benefits the accuracy of the model, see table 1).

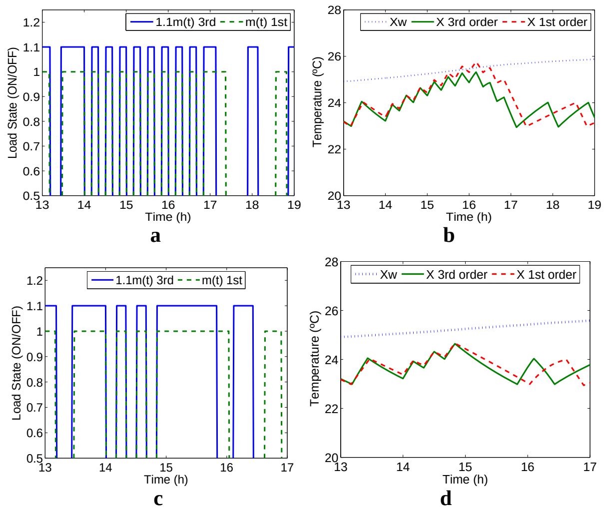

Figure 2. Dynamic of load models: a) load state for DR, T=3h; b) Its temperatures ; c) load state for DR, T=1h; d) Its temperatures.

The differential equation for the model (fig 1) is:

$$\frac{dX(t)}{dt}=\left[-\frac{1}{C_a}\left(\frac{1}{a_w}+\frac{1}{a_{rg}}+\frac{1}{a_g}\right)X\,(t)\right]+\frac{1}{C_a}\Big[\big(H_a(t)+H_r(t)\big)+ \qquad (1)$$

$$+\left(\frac{X_{ext}(t)}{a_g}+\frac{X_w(0)}{a_w}+\frac{X_{rg}(0)}{a_{rg}}\right)+H_{ch}(t)m(t)u(t)\Big]$$

LOAD AGGREGATION

Technical barriers for AS in small customers comprise the cost of ICT, and the difficulty to obtain the response of small loads. To reduce these barriers while meeting the needs of system operations, efficient and "easy" aggregation methods have to be developed.

The aggregation process involves selecting loads with the same end-use (HVAC, WH, TES) in dwellings with similar characteristics, service and location. Right now, the first alternative for the aggregation problem is to solve (1), (or higher order equations, for example in price dr) for each load in a control group and obtain a mean power of the aggregated load (through monte carlo simulation). This procedure needs the simulation of large numbers of loads (100-1000) and a lot of computation time (from the point of view of as). The operating state for a control group (cg) of n loads can be defined as:

$$\overline{m}_{cg}(t) = \frac{1}{N}\sum_{i=1}^{N} m_i(t) \qquad (2)$$

In this paper, an alternative is considered. Each individual load of the control group is seen as a realization of a stochastic process, denoted by $\overline{X}(t)$, which follows the stochastic differential equation:

$$\frac{d\,\overline{X}(t)}{dt} = \overline{A}(t)\,\overline{X}(t) + \overline{B}(t) + \overline{H}_{ch}(t)\overline{m_{cg}}(t)u(t) + W(t) \qquad (3)$$

Where $\bar{A}(t)$ and $\overline{B}(t)$ represent losses and gains of an equivalent load, computed through the average of the parameters in (4) for the loads from i=1 to N:

$$A_i(t) = \left[-\frac{1}{C_a}\left(\frac{1}{a_w} + \frac{1}{a_{rg}} + \frac{1}{a_g}\right)\right]$$
$$B_i(t) = \frac{1}{C_a}\left[\left(H_a(t) + H_r(t)\right) + \left(\frac{X_{ext}(t)}{a_g} + \frac{X_w(0)}{a_w} + \frac{X_{rg}(0)}{a_{rg}}\right)\right] \qquad (4)$$

And, W(t) is a Wiener process with variance σ^2 which takes into account heat gains or heat loss processes which are difficult to forecast and include in the model (e.g. the increase in the number of people in the dwelling, air infiltrations, the change in solar radiation due to clouds in the sky, the change in the rated voltage, …). Values in eq. (3) are obtained through measurement in representative dwellings (see table 1). The values of $H_a(t)$ are shown in fig 4a as an example of the parameters considered in the model. This variable has been monitored during two weeks (i.e. power of appliances inside the dwelling). Figure 3 shows that this variable suits a normal distribution (mean 99W, σ =14.1W). The mean goes to the deterministic part of the model whereas the standard deviation increases W(t). Other parameters and variables (mainly the heat transfer parameters) are obtained through specific software [5]. In this case, the input data are the surface of windows, kind of glazes, materials, latitude, azimuth, etc.

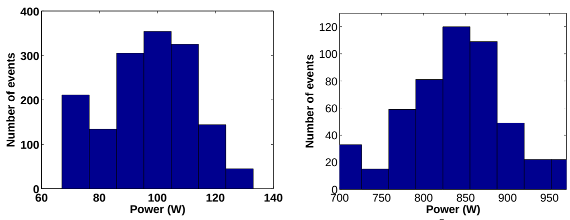

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Figure 3. Two examples of variables used in (3): a) $H_a(t)$, b) $H_{ch}(t)$

The probability density function associated to the stochastic differential equation (3) can be obtained by the following Fokker-Planck equations (see [6]):

$$\frac{\partial f_k(x,t)}{\partial t} = -\frac{\partial}{\partial x}\left[r_k(x,t)\,f_k(x,t)\right] + \frac{\overline{\sigma}_k^2}{2}\frac{\partial^2 f_k(x,t)}{\partial x^2};\quad k = 0,1 \qquad (5)$$

Above, $f_1(x,t)$ denotes the probability density function when the aggregated load given by (3) is switched "on" and $f_0(x,t)$ denotes the same for the "off" state of the aggregated load. That is:

$$f_k(x,t)dx = \Pr\left[x \le X(t) \le x + dx \cap m(t) = k\right]; k = 0,1 \qquad (6)$$

Also, $\overline{\sigma_K}$ represents the instantaneous variance per unit time of the change in X(t), which is estimated from W(t). Finally, $r_k(x,t)$ represents the instantaneous mean per unit time of the change in $\overline{X}(t)$, which is given by:

$$r_k(x,t) = \overline{A} + \overline{B}(t) + \overline{H_{ch}}(t)\,k\,u(t); \begin{Bmatrix} k = 0 \Rightarrow m(t) = 0 \\ k = 1 \Rightarrow m(t) = 1 \end{Bmatrix} \qquad (7)$$

Note that u(t) is the binary control variable, which shows if DR policy is being applied or not. Once $f_1(x,t)$ is computed, the proportion of loads switched "on" at time t can be obtained by integrating $f_1(x,t)$:

$$\overline{m}_{cg}(t) = \frac{1}{N}\sum_i m_i(t) = \int_{-\infty}^{+\infty} f_1(x,t)dx \qquad (8)$$

Sometimes, it is more convenient to work with the distribution function $F_k(x,t)$ associated to each $f_k(x,t)$:

$$F_k(x,t) = \Pr\left[X(t) \le x \cap m(t) = k\right] = \int_{-\infty}^{x} f_k(\lambda,t)d\lambda; k = 0,1 \qquad (9)$$

Figures 4a & b, show two of these functions obtained from the example to be developed in simulation section.

An important concern is that, usually, u(t) is considered a deterministic variable, i.e., we apply the same or different control policies for different loads in the control group. This is not true due to practical problems, firstly latencies in transmission signals present in ICT technologies.

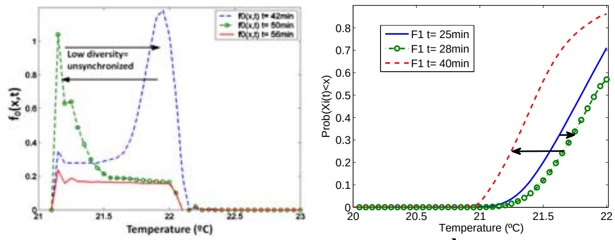

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Figure 4. Probability functions during a control starting at t=15min: **a)** ON density function, **b)** ON distribution function.

This problem has been reported in previous ICT simulation studies [7], and in residential AS pilots [8]. In some of these pilots, latencies affect both the performance of control and ISO requirements (average latency of 69.4s in [8]). The second problem is the lock-out or mechanical delay of HVAC units. This is used to prevent a rapid recycling of a compressor and causes an additional delay to thermostat control signals [9]. Next paragraphs deal with both issues.

ICT Performance and Latency

Figure 5 shows a reference communications architecture, where the main involved actors and the communications networks that connect them are identified.

OpenADR is assumed as application protocol. OpenADR v2.0 is supported by the OpenADR Alliance [10], it has been accepted as standard by standardization bodies such as OASIS and IEC, and it is widely used for DR worldwide. OpenADR defines two types of nodes, namely: VTN (Virtual Top Node) and VEN (Virtual End Node). By combining them recursively, tree-wise topologies can be obtained, as Figure 5 illustrates. The OpenADR server shown in Figure 5 is managed by the ISO and works as VTN in the communication with the OpenADR client, which is managed by the Aggregator.

The OpenADR client, in turn, runs a VEN for communicating with the OpenADR server and a VTN for communicating with the VEN running in the consumption infrastructures managed by the Aggregator.
There are quite a few communications technologies that can be used in each of these communications segments, the selection of the most appropriate ones being influenced by the traffic characteristics and communications constraints of DR [11].

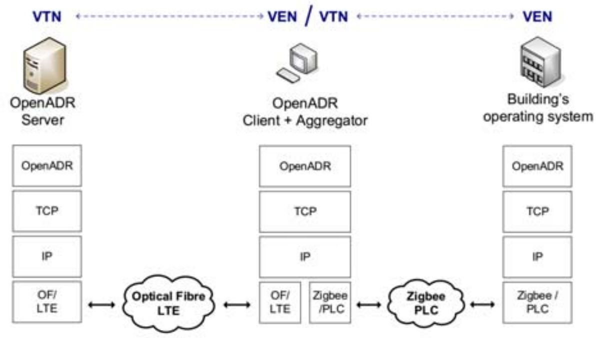

Figure 5. Communications architecture.

On the one side, the ISO and the Aggregators are typically far away from each other. The commands that the ISO sends to the Aggregators may require different time responses, ranging from a few seconds to minutes or even hours or days. Therefore, in this segment, broadband technologies over long distances are required, such as optical fibre or LTE.
On the other side, the Aggregators are typically close to their clients. The Aggregators may monitor the consumption infrastructures they manage by receiving low-frequency messages and may also send them time-constrained commands upon receiving ISO signals. So the volume and the pattern of the traffic are different in the uplink and downlink. In this segment, low-range technologies with lower data rates can be used, such as Zigbee or PLC (Power Line Communications).
PLC technologies are widely used in Smart Grid applications, in general, due to the advantages they present, such as the fact that they use the power cables as communications media [12]. NB-PLC (Narrowband PLC) technologies, in particular, are being widely deployed in the last mile of AMI (Advanced Metering Infrastructure) mostly in Europe and China, but also in the US or Australia [13].
Regarding the application of NB-PLC technologies for DR, availability and latency stand out as key communications parameters.
The availability of this kind of networks is very sensitive to noise. However, the effects of noise can be mitigated by using filters that isolate the domestic electrical infrastructure from the power distribution network. Nevertheless, this would increase remarkably the costs associated to the infrastructure.
As it has already been mentioned, [7] evaluates the performance of OpenADR over NB-PLC infrastructure using as metric the latency under three different types of noise. The results from simulations show that the round-trip latency is very similar for background and synchronous noise (median around 6.5 s and 7.5 s respectively), whereas it is almost double for asynchronous noise (median around 12 s). This paper allows modelling the round-trip latency based on statistical parameters such as the mean and the standard deviation, which may be taken into account as input for the load simulations. However, the main conclusions of this paper are that NB-PLC networks are suitable for DR programs with long lead time, such as day-ahead and day-of DR; whereas the observed latencies may not be appropriate for products in the wholesale ancillary service markets, which require faster communications with demand-side resources.
Therefore, studies similar to the one presented in [7] should be carried out for other communication technologies that offer higher bandwidths. BPL (Broadband over Power Lines) represents a promising solution which may be assessed using the simulator presented in [14], also available on-line [15].

Mechanical latency

Some tests have been done in residential HVAC (inverter) units to consider this issue. For this purpose, several changes in thermostat setting (up & down) were sent to loads, and HVAC demand was recorded with plug meters (pacer trigger 1s). Results are presented in table 2 and compared with times in HVAC units analyzed in [9].

Table 2. Up & down times in response to thermostat changes

Load	Up time	Down time
Residential HVAC (≈ 2kW)	20s-1min	10-40s
Commercial HVAC [9]	≈1min	≈1min

DR SIMULATIONS

Performance ratings of the generation units used in AS are usually determined by means of a test score. For example, in PJM, tests for regulation consist in two normalized signals: Test A (a pulse wave) and Test D (a continuous wave, mainly for storage resources) [10]. Moreover, the resource must be able to respond with 5 minutes (10-15 min for contingencies): consequently, a fast tool which provides understandable results that can be commissioned "just in time" is needed. The objective is evaluating if test signal can be fit through the control of thermostat, with the help of functions (6) & (9). Fig. 6 shows the load response (continuous line) to a hypothetical test signal (dashed line) neglecting delay effects of a residential HVAC group. The increase of demand is "easy" to obtain because the only restriction needed is to raise the thermostat dead-band above the original level (in this simulation example, for heating loads, +1.5ºC at t=15 min).

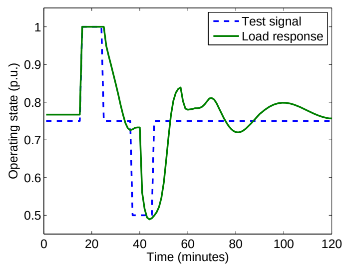

Figure 6. Demand response to a test signal.

It is interesting to explain the use of distribution and density functions (6) & (9) in a simplified way. Let us consider that our control group has 10 loads and each individual load is represented by a ball: green balls are loads in ON (with an indoor temperature, represented in abscissas) whereas red balls are loads in OFF (60/40).
Density function f_1 informs the user (aggregator) about the location (indoor temperature) of a green ball. Distribution function F_1 reports the number of green balls. If the aggregator wants to increase demand from 60% to 80% of rated power, it needs to transform two red balls into green. This can be done increasing the thermostat band above the two red balls on the left band (see fig 7a). This has been solved at t=15min (fig 6) through PBLM simulation software. The increase in set-point drives the increase of green balls temperature too (see fig 7b up).

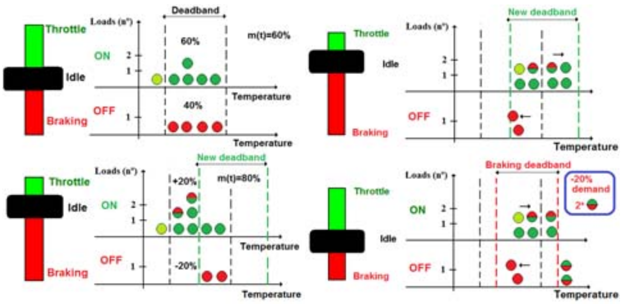

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Figure 7. "Throttle" and "Braking" control of aggregated load through the use of distribution and density probability functions.

The change of test signal at t=25min (fig 6) makes necessary a new change of thermostat. Two green balls should be converted into red, i.e., we need to reduce the thermostat set-point near the left side of the two green balls with the higher temperature (see fig 7b down). This policy makes that two balls (20%) leave dead-band and change their state from ON to OFF. See also, fig. 6 from t=25 to 40min, and note that is difficult to maintain a flat demand in a control group due to its inherent complexity and the dispersion in parameters.
Figure 4b explains the evaluation of thermostat set-points by means of $F_1(x, t)$. In this case, test signal goes down around t=25min, and the aggregator needs to drop demand from 100% to 75%. To do this, he simulates eq. (5) and obtains f_i (x, t) and $F_1(x, t)$ functions. The best scenario for DR performance is to have a flat profile (unsynchronized, see fig. 4a) in $f_i(x, t)$. Then, in $F_1(x, t{=}28\text{min})$ the aggregator finds the x value which gives $F_1(x, t)=0.75$ (75%), i.e., about 21.7ºC.
With respect to delays, some ISOs apply "performance scores" to evaluate customer performance. For instance, delay accounts for 1/3 of revenue in PJM [2]. In our case, a mean delay from 50s to 70s implies that this coefficient drop from 100% to 87%, i.e., revenue fall down a 5%.

CONCLUSIONS

This paper supports new methods of using electricity demand for AS markets. An adapted simulation model, which is well known and has been validated by other DR policies, has been created to evaluate AS response of an important end-use in residential segments: HVAC loads. The advantages of this approach are: the universality of the model (the same database of parameters can be used independently of its objective: AS or other markets); the use of well-known individual models, the robustness of the specific model for AS (i.e., it takes into account important variables), the analysis and consideration of electrical and mechanical latencies, and finally the fast response and interpretation of results. The idea of including communications parameters will make the models and results even closer to reality. Through enabling technology, the participation in AS become possible and this will be valuable for frequency events management in the future.

Acknowledgment

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