

## AGGREGATION OF THERMOSTATICALLY CONTROLLED LOADS FOR FLEXIBILITY MARKETS

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### ABSTRACT

*This paper presents a tool for an aggregator of thermostatically controlled loads (TCLs) to optimally combine their flexibilities into a few representative bids to be submitted to flexibility markets. The tool employs a “bottom-up” approach based on physical end-use load models, being the individual flexibility of each individual TCL simulated with a second-order thermal model describing the dynamics of the house. The approach is based on a direct load control (DLC) of thermostat temperature set-point by the aggregator. End-users receive an economic compensation in exchange for the loss of comfort. The applicability of the proposed model is demonstrated in a simulation case study based on an actual power system in Spain.*

### INTRODUCTION

The replacement of fossil-fuel-based generation by renewable generation is leading to increasingly important challenges in terms of frequency stability, congestion management, voltage regulation and power quality due to its variable behaviour. At the same time, there is a growing penetration of medium and small-scale, flexible demand and storage systems in distribution networks. These resources could potentially be available to provide network services if they are aggregated effectively and if there is an appropriate coordination between transmission systems operators (TSOs), distribution systems operators (DSOs) and aggregators.

The SmartNet project [1] compares five different TSO-DSO interaction schemes and different real-time market architectures [2], [3] with the aim of finding out which one could deliver the best compromise between costs and benefits for the system. For that purpose, an ad-hoc platform has been developed to carry out simulations, and a cost-benefit analysis (CBA) has been implemented to compare the costs needed to implement the five TSO-DSO coordination schemes with the benefits drawn by the system [4]. In parallel, three demonstration projects for testing specific technological solutions are implemented to enable monitoring, control and participation in ancillary services provision from flexible entities located at the distribution level.

The developed platform has been structured in the next three main layers: 1) The “market layer” integrating the

market clearing algorithms, which process the bids proposed by the different players and returns the optimal activations aimed at restoring the system balance and solving/avoiding network congestions; 2) The “bidding and dispatching layer” incorporating the algorithms used by the market players to process the available flexibility of energy resources into bids and to translate the market results into activations; and 3) The “physical layer” simulating the effects of the activations on transmission and distribution networks, including the physics of each (flexible and non-flexible) device connected to them.

This paper describes a tool for an aggregator of thermostatically controlled loads (TCLs) – heat pumps and/or air-conditioning systems – located at distribution level to optimally combine their flexibilities into a few representative bids to be submitted to the real-time flexibility market defined by the SmartNet project called “Integrated Reserve Market” [1]. The tool is integrated into the “bidding and dispatching layer” of the SmartNet simulation platform.

The developed model employs a “bottom-up” approach based on physical end-use load models where the individual flexibilities of the TCLs are simulated with a second-order thermal model describing the dynamics of the house. Control strategies consist of direct thermostat temperature set-point modification by the aggregator between the upper and lower temperature limits previously agreed with end-users who receive an economic compensation in exchange for the loss of comfort.

This is a novel paper focusing on the real-time AS market defined by [1]. The main advantage of the proposed algorithm lays on its simplicity compared for instance with other solutions based on optimization techniques [5]-[9]. In addition, the required accuracy and reliability levels are ensured as they are based on second-order physical models, fulfilling in this way the requirements for being operated in real-time applications.

### INTEGRATED RESERVE MARKET

The flexibility market considered in the SmartNet project, which is called “Integrated Reserve Market”, is aimed at solving real-time imbalances and congestions between intraday markets [2], [3]. The market horizon can vary as a function of the market requirements, but in general it would last from 15 minutes to 1 hour. When a market

session is opened, bidders, which can be conventional and/or distributed energy sources at transmission and distribution networks, are asked to submit their flexibility bids. These can be in both directions, positive or negative, depending if they contribute to upward or downward balancing respectively. Complex bids including temporal and/or logical constraints are also allowed.

## TCLS AGGREGATION MODEL

The developed model uses a bottom-up approach to estimate the aggregated flexibility of a group of TCLs within the aggregator's portfolio. A direct load control (DLC) scheme over the TCLs is considered, where the aggregator can modify the thermostat temperature set-point between the agreed upper and lower limits. Simulation of the individual flexibility profiles corresponding to those control actions is carried out with a second-order thermal model describing the dynamics of the house. Afterwards, the estimated flexibility profiles of all TCLs corresponding to the same control action are added to attain the aggregated flexibility profiles that will represent the final bids to be sent to the market. The bidding price is calculated as a function of the discomfort costs representing the economic compensation that the aggregator gives to the end-users for the supplied flexibility.

### Individual model

The power consumption of a generic TCL  $k$  between time-steps  $t$  and  $t+1$  is simulated with a second-order thermal model based on an equivalent thermal parameter approach (ETP) according to equations (1) and (2):

$$C_{int}^k (T_{int}^{t+1,k} - T_{int}^{t,k}) = [Q_{gains}^{t,k} + \eta^k P_{elec}^{t,k} + \frac{1}{R_{int}^k} (T_{env}^{t,k} - T_{int}^{t,k}) + \frac{1}{R_{ext}^k} (T_{ext}^{t,k} - T_{int}^{t,k})] \Delta t \quad (1)$$

$$C_{env}^k (T_{env}^{t+1,k} - T_{env}^{t,k}) = [Q_{env}^{t,k} + \frac{1}{R_{int}^k} (T_{int}^{t,k} - T_{env}^{t,k}) + \frac{1}{R_{env}^k} (T_{ext}^{t,k} - T_{env}^{t,k})] \Delta t \quad (2)$$

Being:

$T_{int}^{t,k}$	Internal temperature (°C)
$T_{env}^{t,k}$	Envelope temperature (°C)
$C_{int}^k$	Thermal capacity of the internal mass (J/°C)
$C_{env}^k$	Thermal capacity of the envelope mass (J/°C)
$R_{int}^k$	Transfer resistance between the internal mass and the envelope (W/°C)
$R_{env}^k$	Transfer resistance between the envelope mass and the exterior (W/°C)
$R_{ext}^k$	Transfer resistance between the internal mass and the exterior (W/°C)
$T_{ext}^{t,k}$	Outside temperature (°C)

$Q_{env}^{t,k}$	Heat/cool gains due to solar radiation (W)
$Q_{gains}^{t,k}$	Heat gains of the internal loads (W)
$P_{elec}^{t,k}$	Power supplied by the heating/cooling device (W)
$\eta$	Cooling/heating efficiency of the device
$\Delta t$	Duration of the time-step (s)

Knowing the state of the internal ( $T_{int}^{t,k}$ ) and envelope ( $T_{env}^{t,k}$ ) temperatures at time-step  $t$ , the electric power needed by the TCL  $k$  to obtain a certain temperature setpoint  $T_{sp}^{t+1,s,k}$  corresponding to the control action  $s$  at time-step  $t+1$ , can be calculated by setting  $T_{int}^{t+1,k} = T_{sp}^{t+1,s,k}$  and isolating the power variable ( $P_{elec}^{t,k}$ ) in (1).

The estimated power flexibility of the TCL  $k$  at time-step  $t$  ( $P_{flex}^{t,k}$ ), is calculated as the difference between the baseline power consumption ( $P_{bc}^{t,k}$ ) and the actual power consumption with equation (3). The baseline power consumption is an input data and it will normally correspond to the comfort temperature set-point:

$$P_{flex}^{t,s,k} = P_{bc}^{t,k} - P_{ctl}^{t,s,k} \quad (3)$$

The individual flexibility cost is calculated with equation (4) as a function of the discomfort level achieved by the end-user due to the application of the control action and the parameter  $\delta^k$  [€/°C·s] representing the user's sensitivity to temperature discomfort.

$$C_{flex}^{t,s,k} = \delta^k |T_{int}^{t+1,k} - T_{bc}^{t+1,k}| \cdot \Delta t \quad (4)$$

### Aggregation model

The aggregated flexibility and cost curves of the TCLs are estimated using a bottom-up approach. The proposed algorithm consists on an iterative approach to estimate a set of aggregated flexibility profiles corresponding to different possible control strategies that the aggregator can perform over the TCLs. Those strategies are defined by the combination of two parameters: 1) temperature set-point value and 2) duration of the control action.

Temperature set-point values are defined for each particular TCL as a function of their temperature limits ( $T_{sp\_min}^k$  and  $T_{sp\_max}^k$ ) taking into account that they are divided into  $N_{sp}^{prof}$  equal-sized temperature intervals according to equations (5) and (6):

$$\Delta T_{sp}^k = \frac{T_{sp\_max}^k - T_{sp\_min}^k}{N_{sp}^{prof}}; \quad k = 1 \dots N_{TCL} \quad (5)$$

$$T_{sp\_set}^k = \{T_{sp\_min}^k, T_{sp\_min}^k + \Delta T_{sp}^k, T_{sp\_min}^k + 2 \cdot \Delta T_{sp}^k, T_{sp\_min}^k + 3 \cdot \Delta T_{sp}^k, \dots, T_{sp\_min}^k + N_{sp}^{prof} \cdot \Delta T_{sp}^k = T_{sp\_max}^k\} \quad (6)$$

The duration of the control actions is defined in a discrete way varying from one time-step to the maximum possible duration of the control actions ( $N_{ts}^{prof}$ ), which never extends beyond the market horizon. This set is the same for all TCLs. Hence, the total number of possible control actions is the multiplication of all the possible temperature set-point values by the total number of possible durations.

The flowchart in Figure 1 shows the main steps of the proposed algorithm which is based on an iterative approach over the different control durations and temperature set-point levels ( $D_{prof}^n$  and  $T_{sp}^s$  respectively).

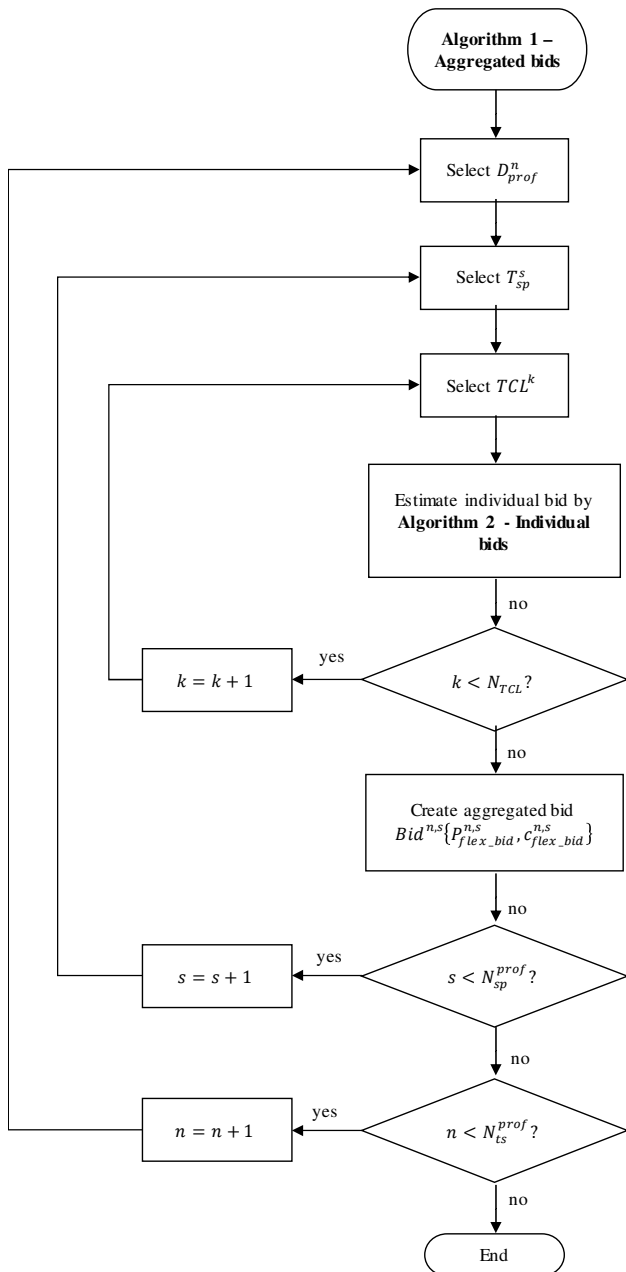


Figure 1- Flowchart for the generation of the aggregated flexibility bids

The method consists of aggregating the individual flexibility profiles simulated for each TCL corresponding to each control action. Individual profiles are simulated with the second-order thermal model presented before for all time-steps included within the market horizon ( $N_{ts}^{tot}$ ) according to Algorithm 2 in Figure 2. From the end of the control action until the end of the market period, there is a rebound period. In this period, the control is returned to the device, which tries to restore the baseline temperature set-point, resulting in a sudden reverse in the direction of the power consumption. Bid price profiles are calculated through aggregation of the individual flexibility and cost profiles corresponding to the considered control action.

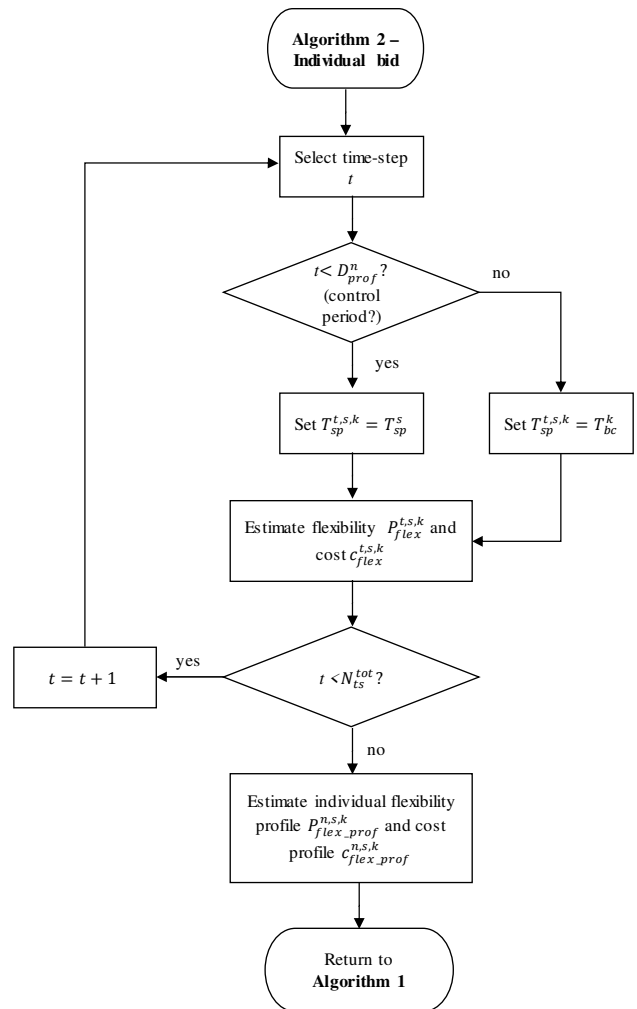


Figure 2- Flowchart for the generation of the individual flexibility bids

The generated flexibility and cost profiles are delivered to the “Integrated Reserve Market” as complex bids, including the following constraints: 1) “non-curtable bids”, meaning that the market operator can either accept or reject the total energy quantity offered; 2) “accept all time-steps or none” to ensure that, if accepted, the bid is accepted for all time-steps considered in the bid; and

3)“exclusive choice constraints”, to indicate an exclusive acceptance between the generated set of bids, as the they are mutually exclusive because they correspond to different control actions over the same set of TCLs.

The disaggregation process after the market clearing is a straightforward step, as the aggregator knows the mapping between the generated flexibility bids and the individual control actions applied.

## CASE STUDY

Simulations on a specific case study based on an actual power system in Spain have been conducted to assess the performance of the proposed algorithm. The case study makes projections of a future spring scenario (year 2030).

### Inputs

It is assumed that the Integrated Reserve Market is called every hour, with a time resolution of 15 minutes, to solve the system imbalance in the considered area.

The aggregator’s TCL portfolio comprises 360 domestic heat pumps whose baseline, minimum and maximum temperatures are considered to be 22°C, 21°C and 23°C for all of them respectively. Outdoor temperature in the considered area for a typical spring day has an average value of 15.7°C. It is assumed that the possible control temperature set-points that the aggregator can apply to the TCLs are 21°C and 23°C respectively. The control durations can vary from 1 to 4 time-steps of 15 minutes, coinciding with the length of the market horizon. This leads to eight possible control actions for each TCL (e.g. 21°C for 1 time-step, 21°C for 2 time-steps, etc.).

This case study focuses on the market session starting at 14:15 and finishing at 15:15, where the power system imbalance to be solved is presented in Table 1.

Table 1 – Power system imbalance

Time-step	Power (MW)
14:15-14:30	-1.184
14:30-14:45	1.868
14:45-15:00	0.057
15:00-15:15	1.057

## Results and discussion

The iterative process presented in Algorithm 1 requires the generation of the individual flexibility and cost profiles for each TCL corresponding to every possible control action, according to the procedure presented in Figure 2 (Algorithm 2). For this purpose, the second-order thermal model is used to simulate the response of each individual TCL to the different control actions. Figure 3 shows an example of individual load demand curves of a heat pump in the base case and in the controlled case when the thermostat temperature is set to 23 °C (+1°C in relation to

the baseline) for 1 time-step (15 minutes). It can be observed that during the first time-step the heat pump increases its power consumption until its nominal power resulting in an indoor temperature increase. Afterwards, the control is returned to the device that attempts to return to the previous state being switched-off.

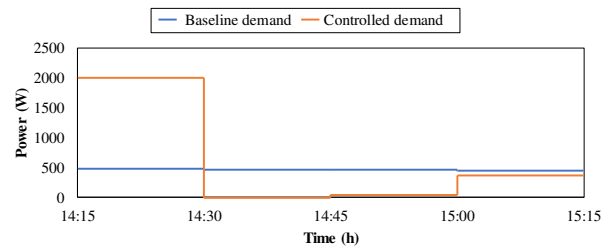


Figure 3 - Baseline and controlled load demand curves for an individual TCL

Based on these results, the individual flexibility bid resulting from the considered control action is presented in Table 2, which is calculated as the difference between the baseline and the controlled power profiles.

Table 2 – Sample of individual flexibility bid profile

Time-step	Flexibility(W)
14:15-14:30	-1521.54
14:30-14:45	466.70
14:45-15:00	408.90
15:00-15:15	84.43

This process is repeated for all TCLs for all possible control actions and, then, the individual flexibility profiles corresponding to the same type of control action are aggregated following the procedure described in Figure 1 (Algorithm 1). The resulting aggregated flexibility profiles are presented in Figure 4. These represent the flexibility bids finally delivered by the aggregator to the market.

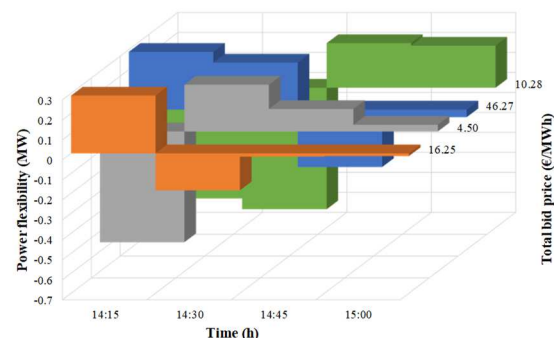


Figure 4 – TCLs flexibility bids for the market period 14:15 – 15:15

For this particular case study, the “bidding and dispatching layer” of the Smartnet simulation platform accepts the second bid represented in Figure 4 (grey profile) in the market clearing result. In the disaggregation process, this bid corresponds to apply a temperature set-point of 21°C for 15 minutes starting at 14:15 to all TCLs in the cluster.

Figure 5 shows the contribution of the overall flexibility accepted in the market to solve the system imbalance in Table 1. It includes a breakdown of the flexibility accepted from the TCLs, as well as from other flexibility providers, such as storage systems, combined heat and power plants (CHPs), curtailable loads and generation, etc.

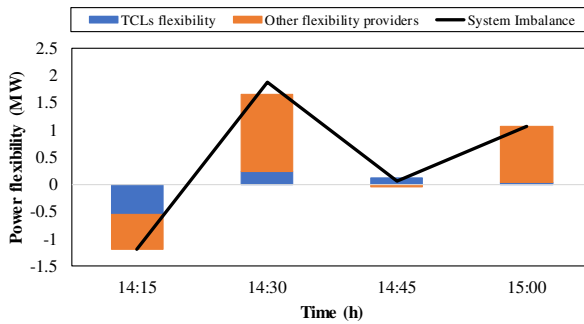


Figure 5 – Flexibility accepted in the market

It can be seen that TCL bids contribute to solving system imbalance in both directions, taking advantage of the rebound period occurring when the control action is released (14:30). It can be concluded that, as an output of the considered market session, the DSO is able to solve the system imbalance expected for that hour.

## CONCLUSIONS

In this paper, a tool for an aggregator of TCLs to optimally combine their flexibilities into a few representative bids to be submitted to a real-time flexibility market designed for the activation of balancing and congestion management services is provided.

The main advantage of this model lays on the simplicity it requires in comparison with models based on optimization techniques, because it is based on direct summation of individual flexibility profiles. At the same time, the required accuracy and reliability levels are ensured, as it makes use of physical end-use models to simulate the behaviour of the TCLs under the different control actions.

Results of the simulated case study have shown the feasibility of the developed algorithm for generating flexibility bids, thus allowing the participation of a portfolio of domestic TCLs in real-time capacity markets.

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