ISSN 1750-9653, England, UK
**International Journal of Management Science
and Engineering Management**
Vol. 3 (2008) No. 4, pp. 243-252

Realtimes dynamic optimization for demand-side load management

Duy Long Ha*, Stéphane Ploix, Eric Zamai, Mireile Jacomino

Laboratoire des Sciences pour la Conception, ÍOptimisation et la Production (G-SCOP) , FRE3028 , BP46, F-38402
Saint Martin d́Hères Cedex, France

(*Received December 14 2007, Accepted March 18 2008*)

Abstract. This paper focuses on Demand-Side load Management applied to residential sector. A multi-scale optimization mechanism for demand-side Load management is proposed. It composes the Load Management Layer, which carries out the distribution of the energy in housing. A dynamical limit for power consumption will be applied to each household. The home automation system integrated in each household plays the role of controlling the whole energy consumption in the housing by using service and appliances flexibilities, thus the energy consumption has the possibilities to be modified and controlled. Thanks to the feedback of the satisfaction of the client by the home automation system, the Load Management Layer can modify the limit of power consumption of the household again. This control mechanism takes dynamically into account the comfort of the users and satisfies the constraint from the energy production capabilities. A simulation of 400 housings points out the performance of this control mechanism.

Keywords: load-Management, home automation, distributed control, multilevel optimization

1 Introduction

Demand-Side load Management (DSM)[14] is a set of methods that co-ordinate the activities of energy consumers and energy providers in order to realize the best adaptation of energy production capabilities for consumer needs. Thanks to DSM, energy demand peaks, which on the one hand, have negative environmental impacts and on the other hand, increase energy production cost[15], can be reduced. In residential sector, the development of Home Automation Systems (HAS) makes it possible for energy consumers to be involved in DSM by adapting their consumption to their production needs[16]. [15] presents basic kinds of DSM control:

- Direct control that shifts power requests by directly interrupting the high power consuming appliances.
- Local control that consists in setting up a policy, which encourages consumption at off-peak periods by reducing energy costs.

However, these kinds of control are not very reactive and do not take into account user comfort. A HAS basically consists of appliances, which are allowed to communicate one each other via a communication This DSM control allows energy providers to charge users for the actual energy production cost in a more precise way.

It also allows users to adjust their power consumption according to energy price variations. In the peak period, the domestic customer would be able to decide whether to wait and save money or to use appliances even so. This strategy is more reactive than the basic DSM control but more complex to control when comfort has to be taken into account.

Energy management can be formulated as a scheduling problem where energy is considered as a resource shared by appliances, and periods of energy consumption are considered as tasks. Generally speaking, these

---

* Corresponding author. *E-mail address*: Duy-Long.Ha@g-scop.fr.

approaches collect consumption activities by scheduling all the tasks as soon as possible in order to reduce the total consumption while satisfying a maximum energy resource constraint. These approaches do not manage the differences between predictions and effective values. [12] proposes a solution based on the one-day user consumption predictions. A parallel and distributed genetic algorithm optimizes the consumption of the buildings in order to adjust appliances consumption to meet energy provider needs. In [6], an adaptation of the static Resource Constrained Project Scheduling Problems (RCPSP) is presented to improve the management of electric heating systems. This approach is able to co-ordinate the electric heaters while satisfying a maximum power resource constrained. Nevertheless, the problem requires precise predictive models and, moreover, it is NP-hard. [5, 7] presents a new three-layer household energy control system capable not only to satisfy the maximum available electrical power constraint but also to maximize user satisfaction criteria. This approach carries out more reactivity for fitting the energy provider needs. Rooms equipped with electric heaters are used to illustrate the capability of the control mechanism in using natural thermal accumulation to adjust power consumption in real time.

Generally speaking, the problem of Direct Loads Controls (DLC) scheduling is largely studied, DLC is the effective load management scheme for curtailing the system peak load involving the air-conditioner or heating water load. The problem is to set the ON/OFF control of the air-conditioner load generally using the dynamic programming to minimize the load reduction cost in [4] or the thermal comfort of the user[3]. The fuzzy logic based approach has been introduced in [13] to improve the estimation of comfort. All those approaches have the same weak points:

- the management the uncertainty and the disturbance: in the case the customer is not in his housing, the energy which is affected for this housing should be released and distributed to another customer.
- the customer's satisfaction is taken into account in a static way (the customer's questionnaire[9])
- the memory requirement of dynamic programming implementation increases 2^n times, where n is the number of interruptible loads. The complexity of the exact algorithm for optimal solving of this problem is $H \times 2^n$[8], so it is very hard to apply those methods to large scale problems.

2 Multilevel control mechanism

The power system is composed of many different elements: different power sources, the distribution system from very high voltage to low voltage which supplies the consumers. Inside a consumer's housing, domestic appliances such as Heat Ventilation and Air Conditioning systems (HVAC) or the lighting and the cooking may be encountered. If a control mechanism takes into account every detail of the power system, from the nuclear plan to each air-conditioner, the problem becomes extremely huge and too complex to be solved. Even if the problem is solved, the real-time constrain is no longer respected. The key idea of multi-level control mechanism is to use several layers of control, which allows the problem to be decomposed into smaller ones and to find a near-optimal solution. Approximate solution must be obtained in real-time and it should take implicitly into account the perturbations. The decomposition into layers of control can either be spatial or temporal.

The model of the system in the highest layer is the most abstract. The one of the lowest layer is the least abstract. A layer at a given level is transparent for higher layers. Layers are connected by the information flows, which consist in constraints, criteria, inter-layer exchanged demands. The use of information flow is inspired from [1], but an amelioration of this idea concerns the multi-layer control conception reducing the "ping pong" effect. The messages are exchanged only from different control layers, not between devices at the same layers. The synchronization and coordination between different layers is achieved by using the information flows. The multi-level control mechanism manages the most abstract level of the system model before entering into detailed problems.

In the context of this paper, two decomposition schemes along spatial and temporal axes have been set-up as Fig. 1. Firstly, a spatial decomposition considers the global system with the load management layer, split up into several households at the home automation layer. In turn, each of these households is decomposed into several devices layer. These layers are synchronized according to two time scales one for anticipative layer and another one for reactive layer. While anticipative layer forecasts the use of the energy, the reactive layer deals with its real-time allocation, following the set points computed by the anticipative layer and takes into account perturbations.

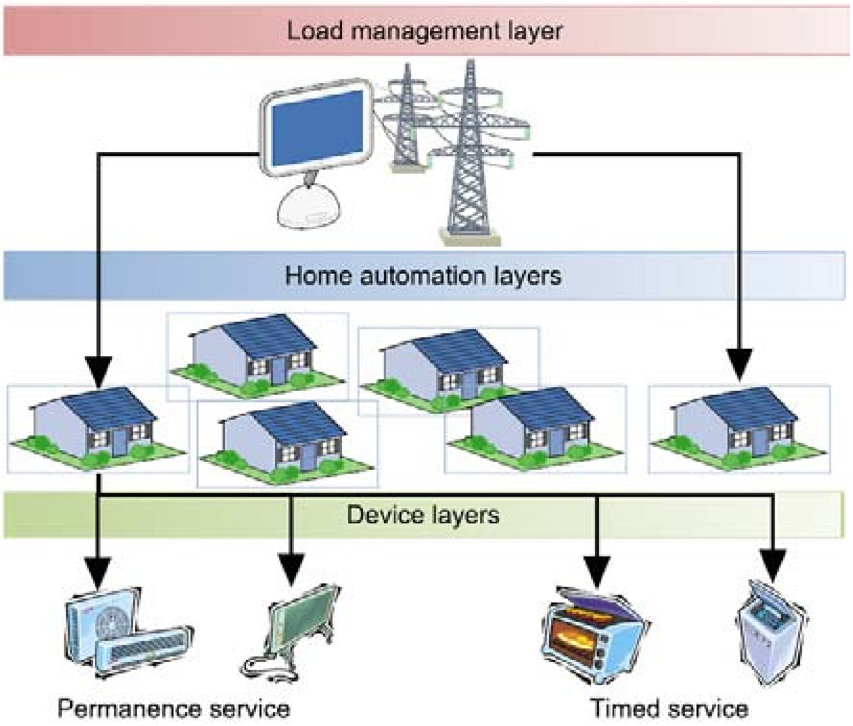

Fig. 1. Control mechanism

2.1 Load Management Layer

This layer is responsible of the co-ordination of the energy consumption of a set of housings by carrying out a dynamic adjustment maximum power consumptions of housings. The consumption of appliances is hidden in the home automation layer, which is transparent for the load management layer. Load Management Layer (LML) is based on the most abstract models. Only information about power allocation and the satisfaction of customers are taken into account by this layer. In order to reduce the peaks of power consumption of a set of housing, the LML is responsible to fix the power consumption limit for each household. By fixing this limit, a new problem may appear: the total power consumption of the housings may not meet the limit that the LML want to set. The power consumption limit has consequently to be adjusted dynamically.

2.2 Home automation layer

The home automation layer is composed of several HAS that distribute the energy to the devices in the households. The relation between the HAS and the housing is one to one.

The anticipative layer for a home automation system is responsible for managing predicted events dealing with electric sources and loads in order to avoid as much as possible the use of reactive layer. The prediction procedure forecasts several events not only about future user requests but also about the future available energetic resources and the fluctuation of the energy price. This layer has slower dynamics than device layer and includes predictive models with learning mechanisms. The detail of method used in anticipative layer is not presented in this paper: refer to [5, 7] for more details.

Objective of the reactive layer is to manage the real-time adjustment of energy allocation. This layer is responsible for making decision in case of violation of predefined constraints dealing either with energy or with comfort. The control actions may either be to enable or to disable controllers of the device layer.

2.3 Device layer

The device layer is composed of devices together with their existing control systems generally embedded into equipment by manufacturers. It is responsible for adjusting device controls to reach the set points given by the anticipative layer of the HAS despite the perturbations. The interest of this layer is to render devices more abstract for the higher layers. Continuous phenomena and fast dynamics are hidden in this layer. An example of device layer is the regulation mechanism of an air-conditioner or an electric heater. The service satisfaction is supposed to be identical for all customers.

3 Problem modeling

To be simulated, the house and the devices (including power sources) needs behavior models. A model of the thermal sensation is also provided, which allows the evaluation of the performance of HVAC services.

3.1 Thermal modeling of the housing

Estimation of a thermal model for a room is studied in the literature. Nevertheless, given the importance of uncertainties in predictions, for example, outdoor temperature, thermal modeling parameters which may cover several hours, a simple dynamic thermal model has been proposed in [11]. Unfortunately, this model cannot represent the dynamic of indoor temperature. The second order model based on an electric analogy in [10] has been preferred:

$$\begin{bmatrix} \frac{dT_a}{dt} \\ \frac{dT_m}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{r_iC_e} & \frac{1}{r_iC_e} \\ \frac{1}{r_iC_i} & -\left(\frac{1}{r_aC_i}+\frac{1}{r_iC_i}\right) \end{bmatrix} \begin{bmatrix} T_a \\ T_m \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{r_aC_i} & \frac{1}{C_i} & \frac{W}{C_i} \end{bmatrix} \begin{bmatrix} T_{out} \\ \phi_r \\ \phi_s \end{bmatrix}$$

This model allows a more precise description of the dynamical variation of indoor temperature with:

- T_a, T_{out}, T_m the respective indoor, outdoor and housing envelope temperature
- C_i, C_e the thermal capacities of indoor environment and of the envelope of the housing
- ϕ_r the energy flow generated by the thermal generator, $\phi_r > 0$ for the case of a heater and $\phi_r < 0$ for the case of an air-conditioning system
- ϕ_s the energy flow generated by the solar radiance

3.2 Device modeling

Service j is supplied by the device j in a one to one relationship. This paper focus on the HVAC system which is modeled by a ON/OFF control. The principle of this type of control is illustrated by the automata given by Fig. 2. In the case of a heater, the thermal generator switches to the ON state when the ambient temperature reaches the lower limit of set-point temperature and switches to the OFF state when the temperature reaches the upper limit. In the case of an air-conditioner, the control objective is to cool the ambient temperature, so the control logic is inverted.

3.3 Thermal sensation modeling

User comfort is a subjective point of view which is difficult to assess. [2] has proposed the ISO7730 thermal comfort standard. The function of PMV (Predict Mean Vote) is determined following this standard. In this paper, only indoor temperature is taken into account for thermal sensation of the HVAC service. Other elements like outdoor temperature, humidity, user's clothes and mean air velocity are assumed to be constant. The ISO7730 standard distinguishes the comfort according to different categories and seasons. For example, in A categories, in the winter, the indoor climate condition must fulfill the following constraints:

- The "ideal" temperature T_{opt} or the most comfortable thermal sensation is 22.5°C

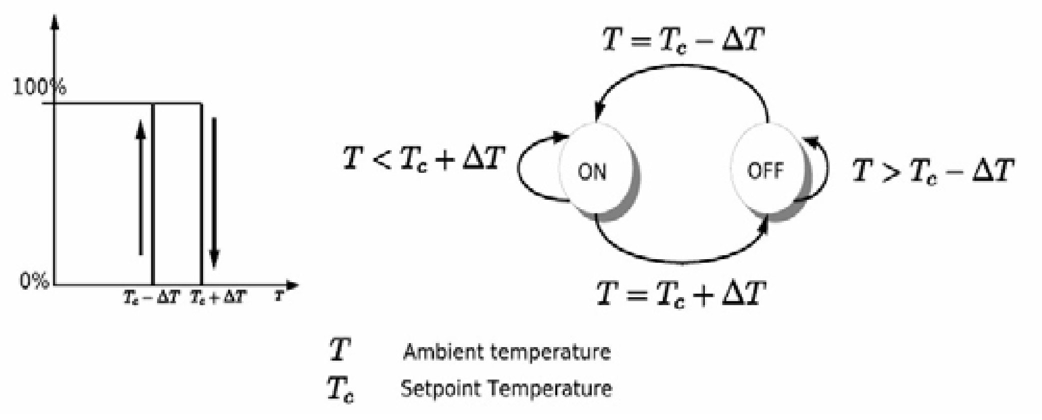

Fig. 2. Finite automata of the on/off control of an electric heater

- The acceptable range of temperature is $T_{min} = 20.5°C \le T(j,k) \le 24.5°C = T_{max}$
- The maximal air velocity is limited to 0.12 m/s

The objective of the HVAC system control is to maintain the indoor temperature around this "ideal" set point temperature T_{opt}. The range of acceptable indoor temperature is determined by $-1 \le PMV \le 1$, and predicted thermal sensation in period is with the index service. The unsatisfied criterions for HVAC service are defined as follows:

$$PMV(T(j,k)) = \begin{cases} \frac{T(j,k)-T_{opt}}{T_{opt}-T_{min}} & \text{if } T(j,k) \le T_{opt} \\ \frac{T_{opt}-T(j,k)}{T_{max}-T_{opt}} & \text{if } T(j,k) > T_{opt} \end{cases}$$

3.4 Power source constraint modeling

For sake of simplicity, all the devices supporting the services on loads are assumed to be purely resistive. Therefore, the total energy consumption of all devices $j, j \in \{1, \ldots, N_j\}$ in the housing $i, i \in \{1, \ldots, M\}$ must satisfy respectively the following constraints:

$$\forall i,\ \forall k \sum^{N_i} P(j,k) \le \overline{P(i,k)}$$

with $\overline{P(i,k)}$ is the upper limit of total consumption of household i at period k which is given by the Load Management Layer, the consumption of all housings denoted $p(j,k)$ must satisfy the constraints of maximum available power:

$$\forall k \sum^{M} p(i,k) \le P_{\max}(k)$$

4 Multilevel optimization formulation

Optimization is performed on the distribution on the distribution and home automation layers at different time scales and using different tools. While the energy distribution layer relies on linear programming, the reactive layer of the HAS uses a dynamic programming strategy.

4.1 Load management layer

Distribution nodes work at the sampling time $\varDelta T$. They are responsible for the distribution of the energy for a set of household $i, i \in \{1, \ldots, M\}$. Thanks to the ON/OFF control of devices in the housing, the variable domain of total power consumption limit $\overline{P(i,k)}$ corresponds to the combinations of the different function states of the device. For the device presented in section 3.2, the size of domain $\overline{P(i,k)}$ is 2^{N_i}. If this problem is formulated as an integer programming, in the worst case, time complexity of an exact algorithm (Branch & Bound for example) is $2^{\sum_{i=1}^{M} N_i}$. As a consequence, a combinatory explosion happens usually in the case of large scale problem.

Therefore, $\overline{P(i,k)}$ is supposed to be continuous variable. Linear programming formulation is chosen over an integer programming one. As a consequence, the difference between the energy consumption limit $\overline{P(i,k)}$ and the actual total power consumption $p(i,k) = \sum_{k=1}^{N_i} p(j,k)$ must be taken into account.

Two distinct problems are presented. The exchange of allocated powers ensures to minimize the wasted power is presented. The regulation of allocated power adapts the power allocation for each housing to optimize their satisfaction and it is introduced afterwards.

4.2 Attributed powers exchange

The principle of allocated power exchange is illustrated in the Fig. 3. Assuming that the Load Management Layer controls the energy consumption of two households. At the sampling period k, $t = k\Delta T$, the allocated powers or the limit of total power consumption are $\overline{P(1,k)}$, $\overline{P(2,k)}$ and the actual power consumption of household 1 and 2 are $P(1,k)$, $P(2,k)$. As $\overline{P(1,k)} \in \mathbb{R}$ $\overline{P(2,k)} \in \mathbb{R}$, they don't match exactly the actual power consumption needs. So, the allocated powers are not explored efficiently. Two households cannot reach potential level of power consumption. The key idea of the exchange of attributed powers is the use of an amount of unused attributed power of household 1 to household 2. It helps the household 2 to reach a higher level of power consumption.

Let's $\eta(i,k)$ denotes the coefficient of efficient of distributed power of the household i at the period k, $\eta(i,k)$ is computed by:

$$\eta(i,k) = \begin{cases} \frac{\overline{P(i,k)}}{p(i,k)} & \text{if } p(i,k) > 0 \\ 0, & \text{if } p(i,k) = 0 \end{cases}$$

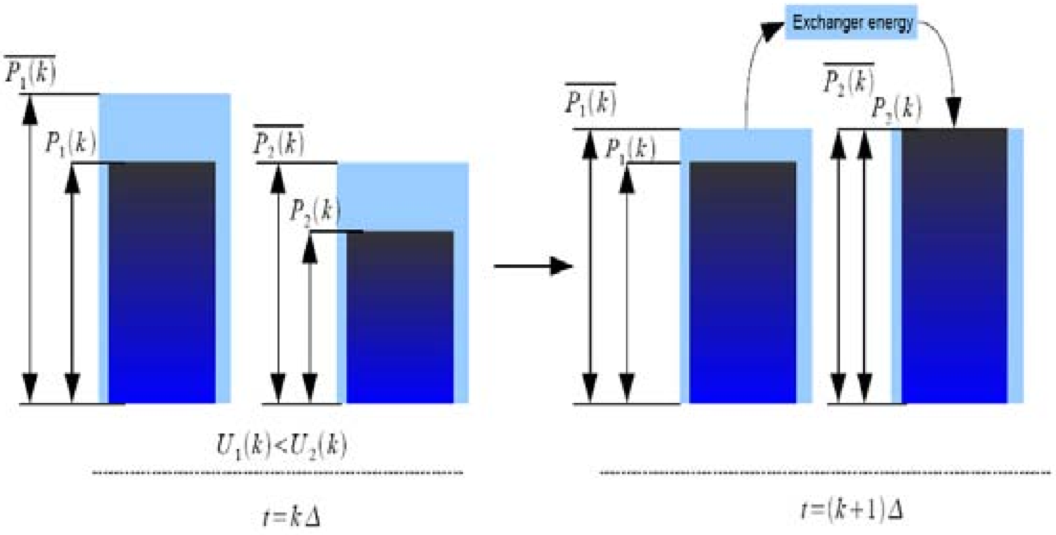

Fig. 3. Principle of attributed power exchange

4.3 Regulation of distributed power

The allocated power $\overline{P(i,k)}$ is adjusted dynamically following the feedback information provided at the sampling period $(k-1)\Delta T$ by the home automation layer, which composes the coefficient of distributed power $\eta(i,k)$ and unsatisfied service $U(i,k)$. The exchange of unused power is achieved by the Linear Programming(LP) as following:

$$\max\{\sum_{i=1}^{M}\eta(i,k-1)\times U(i,k-1)\times\overline{P(i,k)}\}$$

subject to

$$\begin{cases} \sum_{i=1}^{M}\overline{P(i,k)} \leq P_{\max}(k)\forall k \\ LB(P(i,k)) \leq \overline{P(i,k)} \leq UB(P(i,k)) \end{cases}$$

The objective of this LP is to maximize the total efficiency of allocated of allocated power balanced by service unsatisfaction. It explains how the Load Management Layer interprets the satisfaction of the user and the unused power. The coefficient $\eta(i,k-1)\times U(i,k-1)$ is used to apply a heuristic which aims giving priority to the least satisfied and least efficient housing to get more distributed power for this housing. The first constraint corresponds to the available power. The next constraint aims satisfying the constraint of minimum and maximum allocated power to each housing. This linear programming is implemented by using the GLPK solver which interacts with the load management system simulator by a Java interface.

4.4 Reactive layer of home automation system

There are two ways for the home automation system to manifest their satisfaction towards the power supplier at the load management layer: the weighted satisfaction of all services in a household with w_j is the weight of service j.

$$U(i,k)=\frac{1}{\sum_{j=1}^{N_i}w_j}\sum_{j=1}^{N_i}w_jU(j,k)$$

or the worst satisfaction of the set of services inside the housing

$$U(i,k)=\max\{U(j,k), j\in\{1,\ldots,N_i\}\}$$

Therefore, the home automation layer has also two strategies to adjust the power consumption. The first one is to use the total satisfaction. This problem corresponds to the knapsack problem in the literature, a set of objects is needed to push into a knapsack with a limited capacity; the objective is to maximize the total value of whole objects in the knapsack. The second one is to give the priority to the service which has the worst satisfaction. The problem can be solved by a polynomial algorithm.

5 Results

The multilevel optimization has been tested through a simulator on multiple scenarios. The simulator has been written in Java and implements the reactive layers of the load management, home automation and device layers in using a multi-threading design. Two kinds of device have been modeled. The first kind of devices is heaters, providing continuous services of heating the thermal environment. Because there is no anticipative layer, set point for the temperature has been fixed to a constant value. The second kind of device is oven, which provides timed services. Among their parameters there are their period, duration and cooking temperature. The sampling time is chosen equal to 1s.

5.1 Home automation system layer

In the first example, only one housing integrating a HAS has been considered. In this household, 4 heating services provided by 4 different heaters having with maximum power consumption 2kW are considered. In order to show the realtime power distribution of reactive layer of HAS, the power limit is fixed to 2kW. Thus the HAS is responsible for balancing the unsatisfaction of the 4 services while satisfying the maximum power constraint. The thermal room model is:

$$\begin{bmatrix} T_a(k+1) \\ T_m(k+1) \end{bmatrix} = \begin{bmatrix} 0.97 & 0.028 \\ 0.0085 & 0.99 \end{bmatrix} \begin{bmatrix} T_a \\ T_m \end{bmatrix} + \begin{bmatrix} 0.00047 & 0.039 & 0.014 \\ 2\times 10^{-6} & 0.00029 & 6.06\times 10^{-5} \end{bmatrix} \begin{bmatrix} T_{out} \\ \phi_r \\ \phi_s \end{bmatrix}$$

Two scenarios have been considered. The first one simulates the power consumption of the 4 heating services without the HAS. Contrary to the first one, in the second one the HAS is activated. Without HAS, the results are illustrated in Fig. 4, the peak of total consumption reaches 8kW when all heaters consumes at same time. However, at some period, the total consumption is zero because all heaters go off. In the Fig. 5, with the regulation of HAS the peak of total power consumption respects the power limit, i.e. at most, there are only two heaters which consume at the same time. In coordinating the consumption of 4 heaters, the satisfactions of the services are balanced. Small variations of air temperature in the room can be observed but it can be considered as not significant.

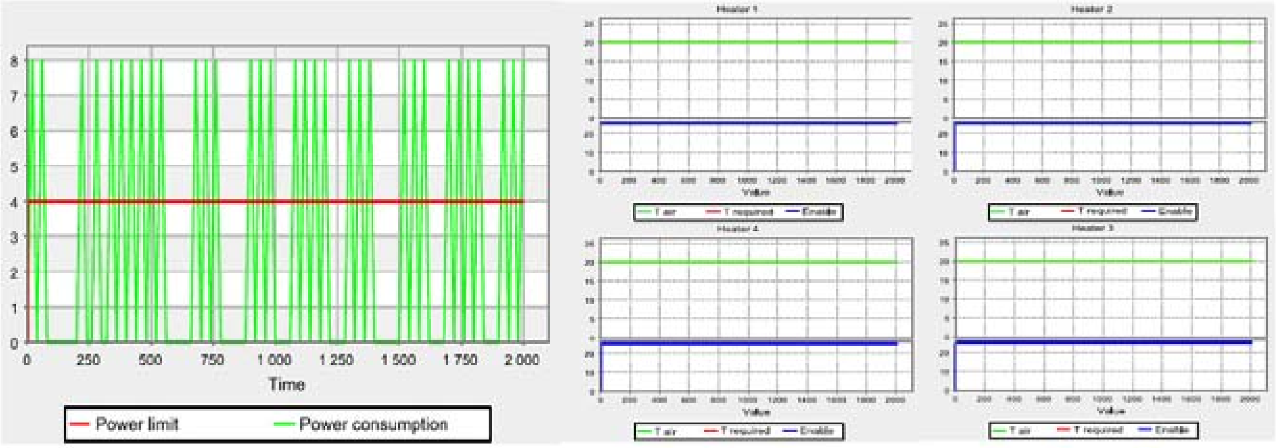

Fig. 4. Results of the case of a household without has

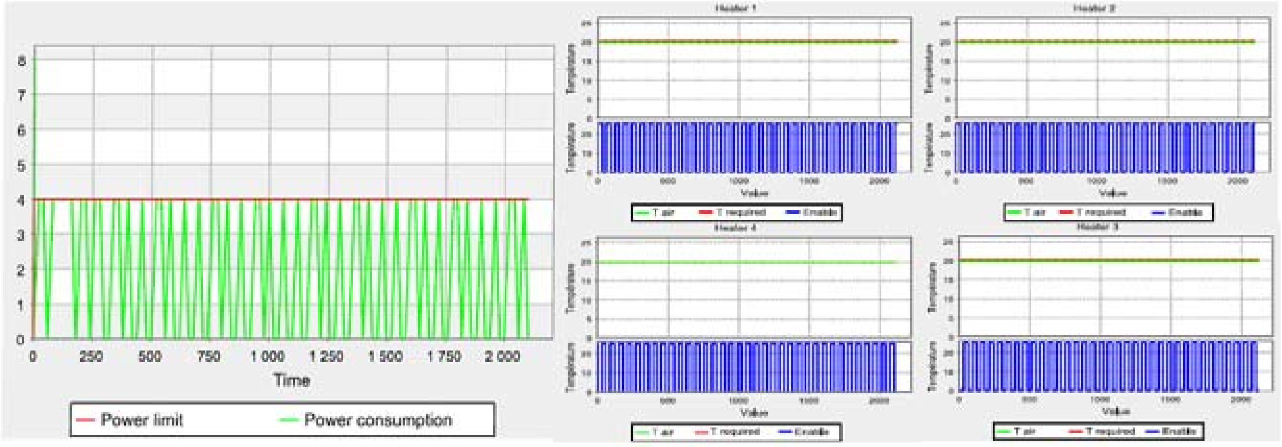

Fig. 5. Results of the case of housing with has

5.2 Large-scale example

This scenario shows the operation of the system and test the reactivity of the control mechanism. Room models have been tailored to get a high dynamic on the heater; temperature drops quickly in order to visualize the reactivity capabilities of the control mechanism. Load management layer provides power to four housings with a subscribed power of 3 or 4kW. In each housing, there are two to four heaters consuming 1 or 2kW as well as an oven. Results of the simulation are shown in Fig. 6 where one can see the power from the load management layer, the power consumed by two housings and the results on two devices from the first housing. At the beginning, total power from the distribution node is set to 15kW, this is sufficient for all the households so no regulation is needed. At time unit 350, available power drops to 8kW, and regulation starts. Power is allocated to each house and there is little effect on the devices. At time unit 750 total power drops to 6kW, and an effect on the temperature can be noticed, but not on the oven. In fact, ovens have been given a higher priority than the heaters.

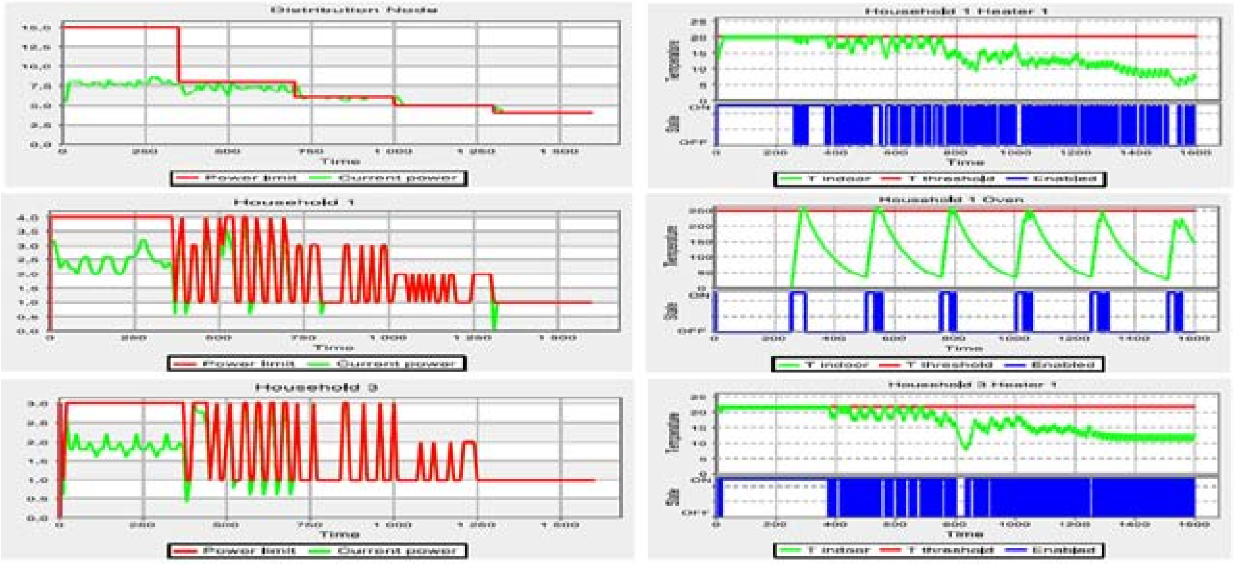

Fig. 6. Results on the four households example

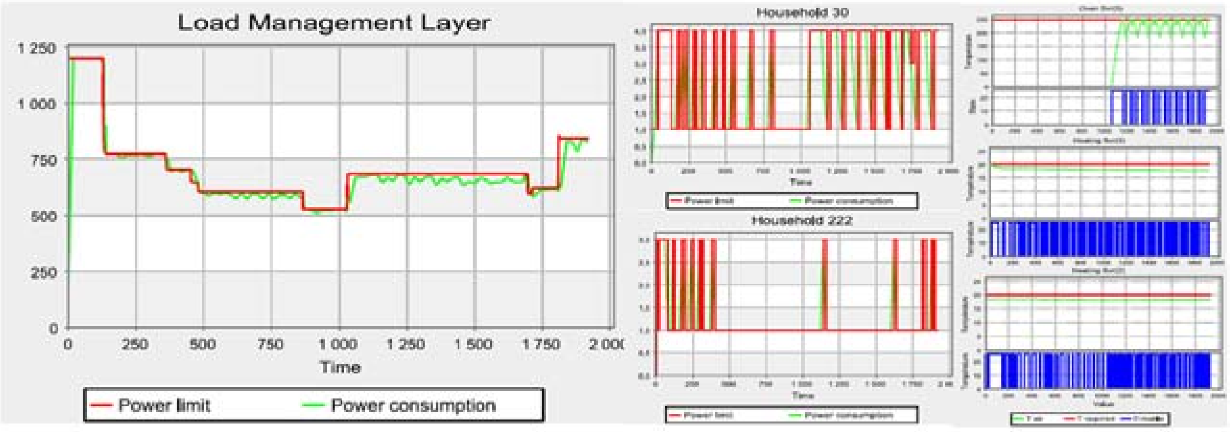

Fig. 7. Results on the 400 household example

6 Conclusions

In this paper, a method for managing power consumption in residential sector has been presented. This problem has been formulated as multi-layer optimization problem. A multilayer control mechanism is proposed composed of the load management layer and HA layers. Household energy management system carries out the settings for energy allocation of the services and also the set points of HVAC services. This mechanism synchronizes the energy consumption of a group of housing while satisfying the maximal power constraint and the user comfort remains at a good level. A multi-threading simulation has been done. The results show that this mechanism can solve in realtime large scale problem (400 households). The proposed solution makes it possible for the private households to automatically adjust their consumption in order to satisfy power constraints and consequently to participate into a DSM system.

References

[1] S. Abras, S. Ploix, etc. A multi-agent home automation system for power management. **in:** *The 3rd International Conference on Informatics in Control, Automation and Robotics*, Setubal, Portugal, 2006.

[2] AFNOR. Ergonomie des ambiances thermiques, determination analytique et interpretation du confortthermique par le calcul des indices pmv et pdd et par des critres de confort thermique loca. **in:** *Norme europeenne, norme francaise*, 2006.

[3] C. Chu, T. Jong, Y. Huang. A direct load control of air-conditioning loads with thermal comfort. **in:** *IEEE Power Engineering Society General Meeting, 2005*, vol. 1, 2005, 664–669.

[4] W. Chu, B. Chen, C. Fu. Scheduling of direct load control to minimize load reduction for a utility suffering from generation shortage. *IEEE Transactions on Power Systems*, 1993, **8**(4): 1525 –1530.

[5] D. Ha, S. P. etc. Tabu search for the optimization of household energy consumption. **in:** *The 2006 IEEE International Conference on Information Reuse and Integration IEEE IRI 2006: Heuristic Systems Engineering*, 2006. September 16-18, 2006, Waikoloa, Hawaii, USA.

[6] D. Ha, S. Ploix, etc. Control of energy consumption in home automation by resource constraint scheduling. **in:** *The 15th International Conference on Control System and Computer Science*, Bucharest, Romania, 2005.

[7] D. Ha, S. Ploix, etc. A home automation system to improve the household energycontrol. **in:** *INCOM2006 12th IFAC Symposium on Information Control Problems in Manufacturing*, 2006, Saint Etienne, France.

[8] Y. Hsu, C. Su. Dispatch of direct load control using dynamic programming. *IEEE Transactions on Power Systems*, 1991, **6**(3): 1056–1061.

[9] K. Huang, Y. Huang. Interruptible load management to provide instantaneous reserves for ancillary services. *IEEE Transactions on power systems*, 2004, **19**: 1626–1634.

[10] H. Madsen. Estimation of continuous-time models for the heat dynamics of a building. **in:** *In Energy and Building*, 1995.

[11] M. Nathan. Building thermal performance analysis by using matlab/simulink. **in:** *Seventh International IBPSA Conference*, Rio de Janeiro, Brazil, 2001.

[12] Y. Penya. Last-generation applied artificial intelligence for energy management in building automation. **in:** *Proceedings of the 5th IFAC International Conference on Fieldbus Systems and their Application*, 2003, 79–83.

[13] H. Salehfar, P. Noll, etc. Fuzzy logic-based direct load control of residential electric water heaters and air conditioners recognizing customer preferences in a deregulated environment. **in:** *IEEE Power Engineering Society Summer Meeting*, vol. 2, 1999, 1055–1060.

[14] B. Thomas. Load management techniques. **in:** *Southeastcon 2000. Proceedings of the IEEE*, 2000, 139– 145.

[15] K. Wacks. Utility load management using home automation. *IEEE transaction on Consumer Electronics*, 1991, **37**: 168–174.

[16] K. Wacks. The impact of home automation on power electronics. **in:** *Applied Power Electronics Conference and Exposition*, 1993, 3 – 9.