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A BUILDING ENERGY MANAGEMENT SYSTEM BASED ON DISTRIBUTED MODEL PREDICTIVE CONTROL

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ABSTRACT

The electrical system is under a hard constraint: production and consumption must be equal. The production has to integrate non-controllable energy resources and to consider variability of local productions. Energy demand is still increasing with larger variability. While buildings are one of the most important energy consumers, they can also be considered as important actors in this problem. Indeed, they have various storage capacities at their disposal : thermal storage, hot-water tank and also electrical battery. The emergence of information and communication technologies (ICT) in the building integrates them as important consumer-actor players in smart-grid. They have the potential to shift, to reduce or even to store [1]. But to ensure their efficiency, it is necessary to develop building energy management (BEM) systems which can interact with the grid and control the building and its systems [2].

In this paper, a BEM system based on distributed predictive control is proposed. The idea is to schedule the actions of the various controllable systems to minimize the energy cost while maintaining the occupant comfort and systems constraints. This scheduling is based on the knowledge of the future data profiles as well as the future cost of energy. The cost reduction is ensured by means of the building storage capacities and by shifting the house consumption periods if the future price is high. Each building is different from another, because of its construction, its systems and its occupants. Consequently, BEM systems have to be modular. This point is ensured by its distributed architecture: one agent is dedicated to each controllable system, and a coordinator agent ensures an optimized global behavior.

Keywords: Building Energy Management, Distributed Model Predictive Control, Load Shedding, Peak Reduction

METHOD

Nowadays, the interest to develop a control for building is to give it the ability to shift or erase its grid consumptions in order to save money and/or reduce its consumption. All this, while ensuring the occupant comfort and system constraints. For that, it is necessary to integrate all the controllable building systems in a BEM system which disposes of a global view.

System formulation

The proposed method is based on a system view of the building installation. It considers that each building system has its own objective and constraints to satisfy. For example, a heating system can be seen as a producer unit, with capacities constraints, which has to ensure the thermal comfort on the building. From a control point of view it is defined as:

Problem 1 Heating System problem :

$$\text{minimize } J = \int_0^H C(t) \cdot P_{hp}(t) dt \quad (1)$$

with respect to $\forall t \in \mathbb{R}$

$$\begin{aligned} Q_{hp}(t) &= \eta P_{hp}(t) \\ \dot{T}_{ambient}(t) &= f(T_{ambient}(t), Q_{hp}(t), B_d D(t)) \\ \underline{P}_{hp} &\leq P_{hp}(t) \leq \overline{P}_{hp} \\ \underline{T} &\leq T_{ambient}(t) \leq \overline{T} \end{aligned} \quad (2)$$

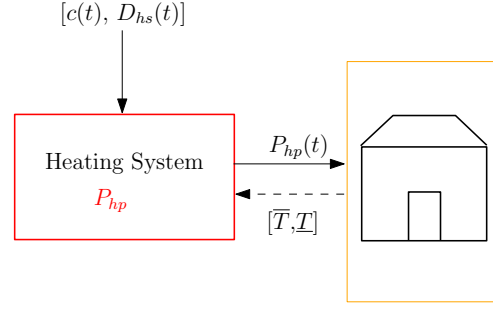


Figure 1: System view example.

where $C(t)$ depends on the control objective. Here, it is supposed to be the time varying energy price. $Q_{hp}(t)$ is the thermal heating power provide through the heating system $P_{hp}(t)$, $T_{ambient}(t)$ is the internal building temperature, $D(t)$ is the uncontrollable thermal gain variable, f is the thermal dynamics coefficients function while \underline{T} , \overline{T} , \underline{P}_{hp} and \overline{P}_{hp} are the temperature and power limits.

From this system view, we define a MPC problem in order to optimize the system consumption during the day.

MPC problem formulation

The model predictive control approach refers to a class of control algorithms that compute a sequence of control moves based on an explicit prediction of outputs within some future horizon.

It consists in solving an optimal control problem, on a finite time horizon knowing the system dynamic models and constraints on states and control variables. Figure 2 sums up the MPC control principle.

Thereby, considering an horizon H , all the equations are discretized at a sampling time T , which is an integer divider of the receding horizon such as $N = \frac{H}{T}$. This leads to define the MPC problem formulation of the example Problem 1.

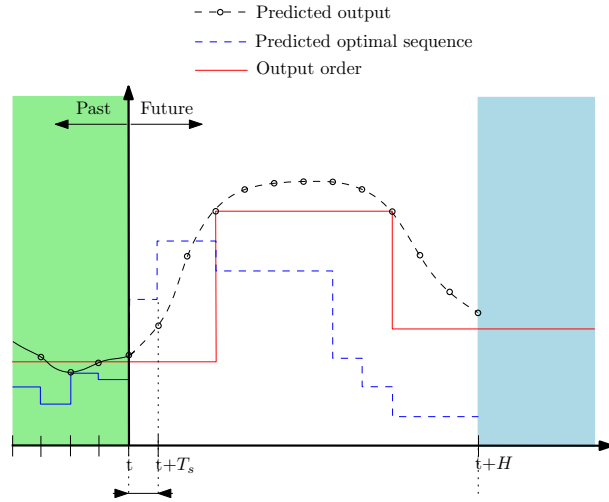


Figure 2: Principle of model predictive control

Problem 2 Heating System MPC problem :

At a time $t = k.T$, given:

- $T_{ambient}(t)$: the current states of the system
- $D_{hs,T}$ and C_T : the uncontrollable variables and the time varying price at the instant

$[t, t + H]$ such as $D_{hs,T}(k) = D_{hs}(t + k.T)$ with $k \in \{0, \dots, N - 1\}$.

and known f_T the discretized dynamics coefficients function of the systems at the sampling time T .

The optimization problem is:

$$\min_{\mathbf{P}_{hp}(0, \dots, N-1)} J = \sum_{j=0}^{N-1} c(j) \cdot \mathbf{P}_{hp}(j) \quad (3)$$

with respect to $\forall k \in \{0, \dots, N - 1\}$:

$$\begin{aligned} Q_{hp}(k) &= \eta \mathbf{P}_{hp}(k) \\ T_{ambient}(k+1) &= f_T(T_{ambient}(k), Q_{hp}(k), D_{hs,T}(k)) \\ \underline{P}_{hp} &\leq P_{hp}(k) \leq \overline{P}_{hp} \\ \underline{T} &\leq T_{ambient}(k) \leq \overline{T} \end{aligned} \quad (4)$$

with $T_{ambient}(0) = T_{ambient}(t)$.

Solving the problem provides, at each sampling time T , the command vector $\mathbf{P}_{hp}^*(0, \dots, N-1)$. Only the first column $\mathbf{P}_{hp}^*(0)$ is sent to the process.

The MPC method enables to anticipate high price period or production period or better systems efficiencies periods. Thus, and thanks to the building storages capacities (walls inertia, batteries, water storage tank, ...), the BEM MPC leads to a shifting strategy [3].

BEM problem

In order to optimize the whole building consumption and to take into account the several interactions between the systems, we formulate the building optimization problem by gathering together all the building installations. Using the previous system view the building optimization problem is formalized as follows:

Problem 3 BEM MPC problem :

The optimization problem is:

$$\min_{\mathbf{U}} J = \sum_{j=0}^{N-1} C(j) \cdot \mathbf{U}(j) \quad (5)$$

with respect to $\forall k \in \{0, \dots, N - 1\}$:

$$\begin{aligned} E_1 u_1(k) &= f_1(k) \\ &\vdots \\ E_i u_i(k) &= f_i(k) \\ &\vdots \\ E_n u_n(k) &= f_{n_s}(k) \\ A_1 u_1(k) + \dots + A_i u_i(k) + \dots + A_n u_n(k) &= M(k) \end{aligned} \quad (6)$$

$$\begin{aligned}
0 &\leq h_1 u_1(k) \leq b_1^{up}(k) \\
&\vdots \\
0 &\leq h_i u_i(k) \leq b_i^{up}(k) \\
&\vdots \\
0 &\leq h_n u_{n_s}(k) \leq b_{n_s}^{up}(k)
\end{aligned} \tag{7}$$

such as, E_i , f_i , h_i and b_i^{up} are the dynamics coefficients and constraints $\forall i \in [1, \dots, n_s]$, A_i refer to the global coefficients and M the global constraints, n_s corresponds to the number of installations.

This (block-angular) problem is effectively solved by the Dantzig-Wolfe method (see [4] for details). This distributed resolution method is exact (gives an optimal solution) and enables to bring modularity to the BEM system control structure (see Figure 3).

Each sub-system is independent, it has its own objective and constraints, and is only connected to the coordinator. The latter has to ensure the global building objective and common constraint.

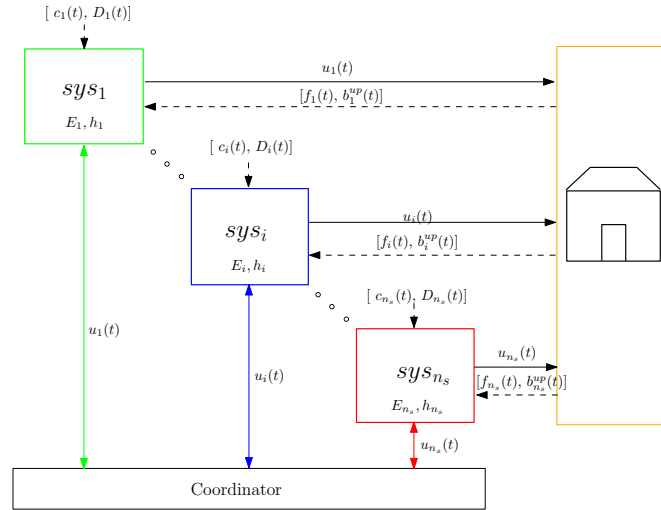


Figure 3: Global system view

The modularity aspect is linked to the system integration. We can note that if we add, delete or modify a system, the concerned system only has to be treated and linked to the coordinator.

SIMULATIONS AND RESULTS

In order to evaluate the adaptability and the efficiency of the proposed BEM control, it has been implemented, in simulation, on two buildings; from one thing the house A, a very inert residential house with very low thermal losses, composed principally of hydraulic radiators, an heat pump (air/water) and a solar water panel combined to a hot water sanitary storage tank; and from another, a high insulated house B with less inertia than the the house A, composed of electrical radiators, a battery, an electrical solar panel and an electric hot water sanitary storage tank.

The simulation scenarii have been performed with disturbances on the data predictions

Daily period (hour)	0 ... 6 ... 13 ... 15 ... 17 ... 19 ... 22 ...
Prices values period	LP HP LP HP CPP HP LP

Table 1: Prices profiles, LP is the Low Price period (0.09€/kWh), HP is the High Price period (0.11€/kWh) and CPP the Critical-Peak Pricing period (0.21€/kWh).

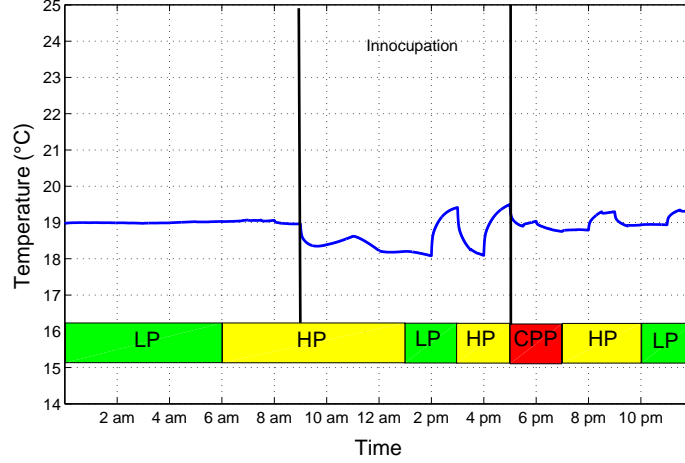


Figure 4: Internal air temperature of the house A regulation

profiles, and the simulation models of the process are not the ones implemented in the controllers but are from the SIMBAD library, a Matlab-Simulink toolbox, dedicated to the building behavior, developed by the CSTB. The temperature set point is set to 19 °C during the occupation period and is free during the inoccupation period.

In this article, we proposed to evaluate the BEMS behavior of the two buildings in response to electricity tariffs profiles.

The simulations results highlight two different strategies. The internal temperature regulation does not vary a lot in the house A (see Figure 4). This is due to its strong inertia and its small heating capacities. Moreover, without electricity storage, the house A regulation is seen as a smoothing strategy even if the hot water tanks are warmed during the LP period.

But, the house B strategy is different. The BEM regulation leads to decrease the temperature until 16 °C during inoccupation period (Figure 5). This is due to its smaller thermal inertia. Moreover, thanks to the battery, the house B changes its heating electrical source and so decreases its impact/consumption on the electrical network. It notes, on figure 6, that the BEM control anticipates the HP periods storing energy in the different systems during the LP period. This leads to shift the building grid consumption. The tariff profile acts as a load shedding strategy.

CONCLUSION

This study proposed an adaptable BEM structure to optimize the energy consumption of residential houses. The modularity is brought by a systemic view combined with a distributed resolution approaches using Dantzig-Wolfe method. For this article, this BEM system architecture, based on MPC, is implemented on two different residential houses.

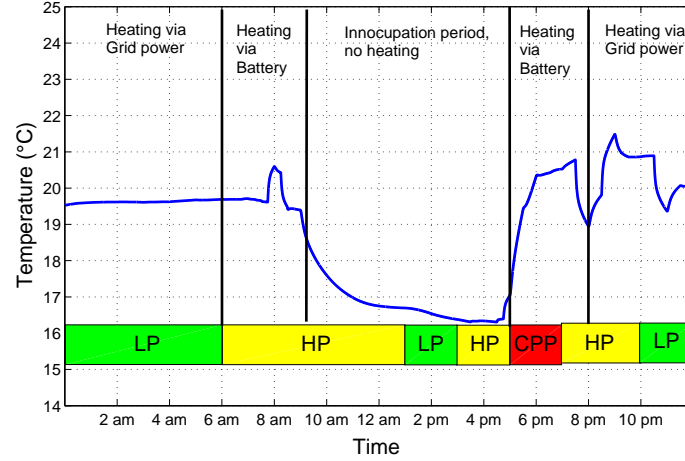


Figure 5: Internal air temperature of the house B regulation

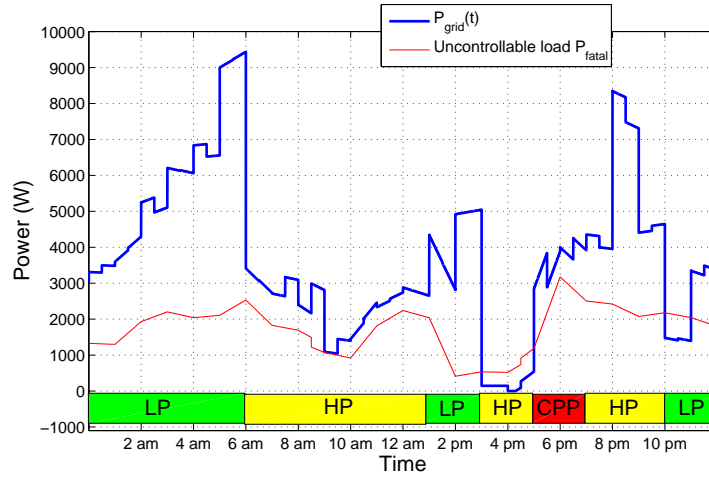


Figure 6: Electrical power consumption P_{grid} from the grid of the house B

The study highlights that the control performance strongly depends on the building characteristics. For a high insulated house with slow dynamic systems, the optimal control results in smoothing of the load, whereas, for a less insulated house with faster dynamic systems, it results in a more reactive control which shifts the peak load consumption.

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