

Integration of low level controller constraints in supervisory control of buildings

Kate Chan Shin Yu* Romain Bourdais* Hervé Gueguen*
Didier Dumur**

* IETR - Supelec, Avenue de la Boulaie, CS 47601 35576 Cesson
Sévigné Cedex - FRANCE (e-mail:

kate.chan,romain.bourdais,herve.gueguen@supelec.fr).

** E3S - Supelec, Plateau de Moulon, 3 Avenue Joliot-Curie, 91192 Gif
sur Yvette Cedex - FRANCE (*didier.dumur@supelec.fr*)

Abstract:

Model Predictive Control (MPC) has been widely used and proved efficient in the control of building installations. It is particularly efficient in the supervisory control of equipment since it can integrate economic, social and environmental dimensions in the computation of the control input. In practice, these equipment possess their own devoted and integrated controllers, which include power saturations and operating modes. Therefore, equipment's inputs cannot be directly controlled by supervisory controllers. This paper aims at analysing to what extent MPC controllers can incorporate existing integrated controllers without introducing extra complexity to their strategies. A Proportional-Integral (PI) controller, with an anti-windup mechanism, has been implemented as the so-called integrated controller. A proposed MPC strategy is discussed. Despite the hybrid functioning of the PI controller, it maintains the simplicity of the problem solving. Furthermore, a comparison between the performances of a benchmark MPC controller (which would drive directly an equipment possessing no integrated controller) and the developed MPC controller is presented. For this study, an office building is targeted and the heating issue has been addressed.

Keywords: Model Predictive Control ; Proportional-Integral control ; Anti-windup ; Hierarchical control ; Building Energy Management.

1. INTRODUCTION

Whatever the purpose for which buildings are built (residential, office, etc.), they must ensure at all times appropriate comfort, functionality and security required by the occupants. Even though new architectural designs, techniques and materials used for construction helped improving users needs, they still prove being insufficient during building's utilisation. In order to make up for this shortage, energy-greedy equipment had to be used. But then, improper control of these can lead to the consumption of excessive amounts of energy. Some updated statistics (2013) in France revealed a raising 43% of the total energy consumption due to buildings [MEDDE, 2013]. Today, economic, social and environmental issues compel the mastering of buildings energy consumption. In this acute context, more and more controllers for these equipment are being studied and developed.

Among the most popular controllers developed for buildings, predictive-based controllers found their place [Old-

ewurtel et al., 2012, Kolokotsa et al., 2009]. Model Predictive Control (MPC) is a predictive-based controller which, first of all, inherently handles multi-variable systems, especially when state-space models are used. This is a major way-out for the control of building systems which, most of the time, require multiple inputs and can deliver multiple outputs. Secondly, a lot of information and data can be gathered from building systems and on the way they are used. These information and data allow sharper selections of influencing parameters as well as the development of accurate models for the anticipation of future behaviours. Thirdly, MPC also inherently handles constraints and it is well known that buildings are highly constrained systems. Not only are they constrained by physical limits but also by operative restrictions. Last but not least, a major asset of MPC is its ability to take into account any desired criterion to be optimised while computing the solution. In this sense, it is highly attractive as a controller to be able to integrate economic, social and environmental aspects into the problem solving.

Despite the mentioned benefits of predictive control for buildings, few implementations have actually been realised [Dounis and Caraiscos, 2009]. The main reason put forward is the dependence of MPC controllers on models. Indeed, building modelling and model identification is still

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an issue [Lin et al., 2012, Privara et al., 2013]. Furthermore, since, in most cases, these advanced controllers aim at reducing the energy consumption, they normally provide the optimal power to be supplied directly to the equipment. In doing so, at least two practical aspects are neglected. First of all, equipment usually integrate their own devoted controllers. Their task is mainly to track given set-points *i.e* rejecting disturbances. They are often simple automations which include power saturations and operating modes. From there, it is nearly impossible to have direct control of the power input. The second aspect deals with the high level of complexity of these advanced controllers which then require important computational means. Both aspects represent, in one way or another, additional economical costs which industrial actors are not ready to pay for.

Taking into account those hindrances, an MPC controller driving an integrated controller, as described above, through a hierarchical structure [Eynard et al., 2013, Singh et al., 2013] could be considered. With an intermittent energy management strategy [Hazyuk et al., 2012], such integrated controllers tend to activate their different operating modes. Consequently, the main difficulty would lie in the integration of all these operating modes into the MPC strategy without increasing its design complexity. The aim of this paper is, thus, to tackle this issue. A Proportional-Integral (PI) controller with an integrated anti-windup mechanism, described in [Astrom and Rundqwist, 1989], is implemented as the so-called integrated controller. We referred the MPC controller which drives directly the equipment as the 'benchmark controller'. The one which drives the integrated controller is referred as the 'MPC-PI controller'. A comparison between the performances of the two controllers is then discussed. For illustration purposes, an office building open-space is targeted and the heating issue is addressed.

This paper is organised as follows. The case study is exposed in section 2 followed by the description of the benchmark controller in section 3. The developed MPC-PI controller is detailed in section 4. A comparison of the controllers performances is discussed in section 5 followed by conclusions and future work in section 6.

2. CASE STUDY

We focused our study on office building heating issues. We considered an open-space, as illustrated in figure 1, located at the first floor of an office building globally well isolated. The installation comprises several equipment. Pointing out, computers, printers and all the office devices, as well as lighting, emit heat energy which we name internal gains. Internal gains also include occupants own heat emission. Ventilation, with its integrated heat exchanger, is never cut off and works intermittently. However, its output flow rate, which causes the air circulation in the room, is always low enough to have negligible effects on the room temperature, as explained later on. An electric heater, with a maximum heating power of 12588 W, is to be controlled by the subsequent controllers. The power that can be supplied to the equipment is therefore bounded as expressed in (1).

$$u_{ht_{\min}} \leq u_{ht} \leq u_{ht_{\max}} \quad (1)$$

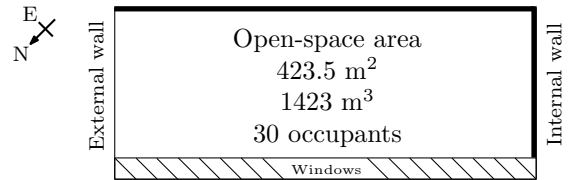


Fig. 1. Studied environment

Even though this particular building exists and is operating, it was much simpler in terms of implementation and testing to work on a simulation basis. Consequently, all of the open-space and associated equipment characteristics were used for simulations with the Matlab/Simulink building toolbox Simbad [CSTB].

A one-week scenario was picked from winter weather data of Trappes (France) and corresponding building's operating data. Prime influencing weather parameters of this scenario are depicted in figures 2a and 2b. The internal gains related to the scenario are depicted, as well, in figure 2c.

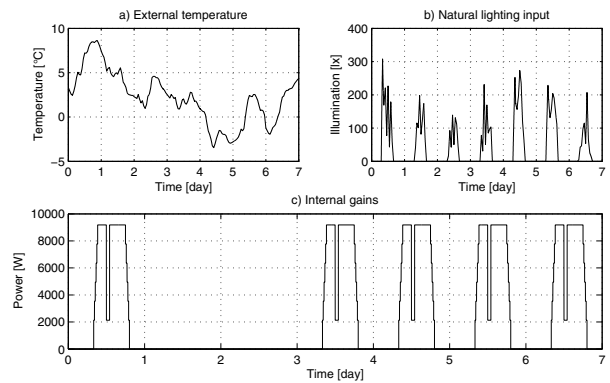


Fig. 2. One-week scenario

One striking point that can be observed in offices is that the occupancy is pretty well set through fixed working hours to conform to. Consequently, interesting control strategies will ensure occupants' thermal comfort solely during opening hours *i.e* with an intermittent heating control of the room [Hazyuk et al., 2012]. The subsequent control laws will be developed, based on this energy management strategy.

The control laws will be set on the operative temperature [ASHRAE, 2010] or, what we commonly call, the room temperature. The operative temperature, T_{op} , is a complex evaluation of the temperature felt by occupants. Provided that certain conditions are satisfied such as low air speed in the room, the operative temperature's expression can be simplified to equation (2)

$$T_{op} = \frac{T_{air} + T_{mr}}{2} \quad (2)$$

where T_{air} is the air temperature of the room and T_{mr} is its mean radiant temperature. The occupants' thermal comfort is defined by a comfort zone expressed in (3) with $T_{op_{\min}} = 19.5^{\circ}\text{C}$ and $T_{op_{\max}} = 20.5^{\circ}\text{C}$.

$$T_{op_{\min}} \leq T_{op} \leq T_{op_{\max}} \quad (3)$$

The aim of the controllers is to regulate for the least possible amount of energy to satisfy the occupants' thermal comfort.

3. BENCHMARK CONTROLLER

The benchmark controller is an MPC controller driving directly an equipment which does not integrate any devoted controller. The benchmark control scheme is depicted in figure 3. The MPC controller, having direct access to the power input, provides the power u_{ht} to be supplied to the equipment.

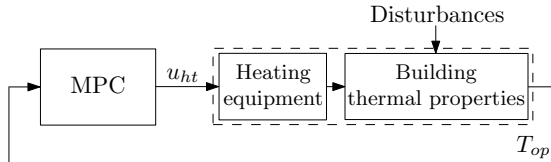


Fig. 3. Benchmark control scheme

MPC technique has been thoroughly explained throughout the literature, *e.g.* [Camacho and Bordons, 2004]. In the sequel, we will rather focus on the adaptation of the general technique to the studied issue.

MPC is a model-based controller. A linear dynamic discrete-time state-space model is chosen. It comprises both the thermal behaviour of the studied room and the heater's dynamic behaviour. It is identified with a fit of 96% by means of a predicted error method [Ljung, 1999]. It is represented in equation (4) with $x_b \in \mathbb{R}^4$.

$$\begin{aligned} x_b^{k+1} &= A_b x_b^k + B_{b_{DV}} u_{DV}^k + B_{b_{u_{ht}}} u_{ht}^k \\ T_{op}^k &= C_b x_b^k \end{aligned} \quad (4)$$

where k is the abbreviation for kT_s with $k \in \mathbb{N}$ and T_s being the model sampling time. For the scenario, T_s equals to 30 minutes. It is chosen at a low sampling rate in order to limit the computational load. The disturbances are represented by u_{DV} . Due to the building orientation and the considered winter season, external temperature and internal gains are major disturbances to the control of the room temperature.

A prediction of the future behaviour of the room temperature is computed with available models of all the disturbances. The prediction horizon as well as the control horizon are chosen equal and given by $N \in \mathbb{N}^*$. For the scenario, because of the intermittent heating and the high thermal inertia of the building, the horizon must be reasonably long enough to enable the heating up of the room after long periods of inoccupancy without demanding important computational means. We fixed $N = 48$ *i.e.* a horizon of 24 hours. This chosen value is discussed in more details in section 5.

We intend to meet the thermal comfort requirements expressed in (3) exclusively during occupancy while the power that can be supplied to the heating equipment is always constrained as expressed in (1).

The core part of the MPC is the optimisation process where a control sequence is generated from the minimisation of a given objective function. We define as the objective function the energy consumption from the power

supplied. A linear cost function is hence chosen since a physical meaning is given to the function to be minimised. The overall problem formulation is presented in expression (5). The current state x_b^k , the forecast disturbances $u_{DV}^{k:k+N-1|k}$ and the predicted state of occupancy $occ^{k+1:k+N|k}$ are given. The notation $k:k+N-1|k$ stands for "from instant k till instant $k+N-1$, all defined at instant k ". The optimal value J is obtained with a linear programming algorithm.

$$\begin{aligned} J &= \min_{u_{ht}^{k:k+N-1|k}} \mathcal{C}^T u_{ht}^{k:k+N-1|k} \\ s.t. \quad x_b^{k|k} &= x_b^k \\ \forall j \in k \dots k+N-1 \\ x_b^{j+1|k} &= A_b x_b^{j|k} + B_{b_{DV}} u_{DV}^{j|k} + B_{b_{u_{ht}}} u_{ht}^{j|k} \\ T_{op}^{j+1|k} &= C_b x_b^{j+1|k} \\ u_{ht_{\min}} &\leq u_{ht}^{j|k} \leq u_{ht_{\max}} \\ T_{op_{\min}} &\leq T_{op}^{j+1|k} \leq T_{op_{\max}} \quad \forall j \setminus occ^{j+1|k} \neq 0 \end{aligned} \quad (5)$$

where \mathcal{C} is the constant weighting vector describing energy consumption. When $occ^j = 0$, this means that the room is forecast to be unoccupied at future instant j .

The resulting room temperature profile and power supplied by the benchmark controller are depicted in figure 4. Performances of the controller will be discussed in section 5.

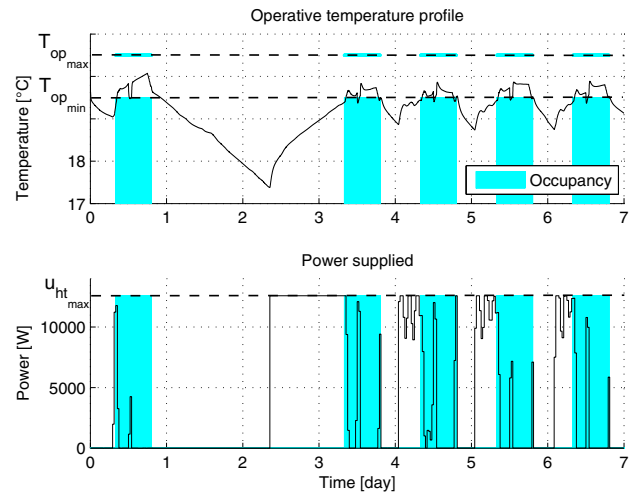


Fig. 4. Results of applied benchmark controller

4. MPC-PI CONTROLLER

4.1 Hierarchical structure

The MPC-PI controller is an MPC controller driving the integrated controller of an equipment *i.e.* in our case, a PI controller. The MPC-PI scheme is depicted in figure 5. Since the optimisation objective is still to minimise the energy consumption, feedback of the actual power u_{ht} supplied by the PI controller to the equipment is required. The MPC-PI controller can only get information about this power supplied but cannot control that input directly. It can only provide temperature set-points T_{sp} to the PI controller which will in turn, drive the equipment.

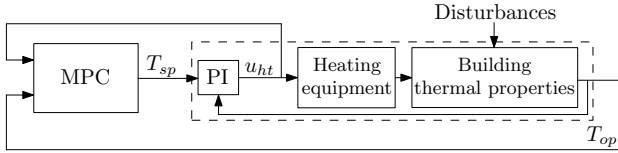


Fig. 5. MPC-PI control scheme

4.2 PI controller

The implemented PI controller consists of a classical proportional-integral action to which an anti-windup mechanism is grafted because of the power saturations inherent to the heating equipment. Its scheme is depicted in figure 6.

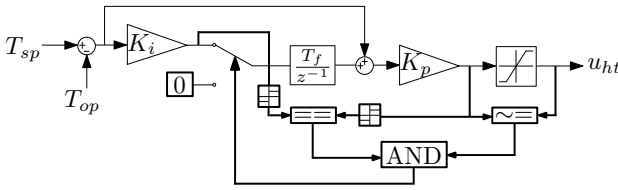


Fig. 6. PI controller with an anti-windup mechanism

where $K_i = 2.2 \times 10^{-4}$ and $K_p = 1.6$. This tuning is chosen in such a way to ensure the system's stability and is not discussed any further in this paper. For the scenario, the control sampling time T_f equals to 1 minute. It is chosen at a high sampling rate in order to reject fast varying disturbances efficiently. The functioning of the PI controller is described in expression (6).

$$\begin{aligned} x_p^n &= T_{sp}^n - T_{op}^n \\ u_{ht}^n &= K_p(x_p^n + x_i^n) \\ \text{if } u_{ht}^n &< u_{ht_{\min}} \text{ or } u_{ht}^n > u_{ht_{\max}} \\ &\text{and } \text{sgn}(x_i^n) == \text{sgn}(T_f K_i (T_{sp}^n - T_{op}^n)) \\ &\text{then } x_i^{n+1} = x_i^n \\ \text{else } x_i^{n+1} &= x_i^n + T_f K_i (T_{sp}^n - T_{op}^n) \end{aligned} \quad (6)$$

where n is the abbreviation for nT_f with $n \in \mathbb{N}$.

Since the room is intermittently heated, frequent overshooting effects caused by the power saturations could occur. The anti-windup mechanism prevent these effects by stopping the integral action [Astrom and Rundqwist, 1989].

4.3 Basic strategy

The MPC-PI controller is an adaptation of the benchmark controller to the new control scheme. Two MPC strategies are proposed with the main one called the basic strategy.

First of all, the integration of the PI controller into the MPC strategy requires a prediction model of the closed-loop behaviour to replace the previous open-loop model expressed in (4). Because of the multiple behaviours of the PI controller, a hybrid model of the PI control is required. This heavy model demands, at the optimisation level, complex and dedicated solvers causing important computational loads and even possible oscillating solutions in case of commutations. Consequently, the PI control is modelled simply by its linear action. It is also re-sampled

at T_s in order to limit the computational load. The PI control model is expressed in (7).

$$\begin{aligned} x_p^k &= T_{sp}^k - T_{op}^k \\ x_i^{k+1} &= x_i^k + T_s K_i (T_{sp}^k - T_{op}^k) \\ u_{ht}^k &= K_p (x_p^k + x_i^k) \end{aligned} \quad (7)$$

In order to keep the implemented PI controller within its linear band, the control input of the MPC strategy is constrained by the power limits expressed in (1).

The resulting closed-loop model is expressed in (8) with $x = (x_b^T \ x_i^T)^T$ and $x \in \mathbb{R}^5$.

$$\begin{aligned} x^{k+1} &= Ax^k + B_{DV} u_{DV}^k + B_{T_{sp}} T_{sp}^k \\ (T_{op}^k \ u_{ht}^k)^T &= Cx^k + D_{DV} u_{DV}^k + D_{T_{sp}} T_{sp}^k \end{aligned} \quad (8)$$

with

$$\begin{aligned} A &= \begin{pmatrix} A_b - (K_p B_{b_{u_{ht}}} C_b) & K_p B_{b_{u_{ht}}} \\ -T_s K_i C_b & \mathbf{1} \end{pmatrix} & B_{DV} &= \begin{pmatrix} B_{b_{DV}} \\ 0 \end{pmatrix} \\ B_{T_{sp}} &= \begin{pmatrix} K_p B_{b_{u_{ht}}} \\ T_s K_i \end{pmatrix} & C &= \begin{pmatrix} C_b & 0 \\ -K_p C_b & K_p \end{pmatrix} \\ D_{DV} &= (0) & D_{T_{sp}} &= \begin{pmatrix} 0 \\ K_p \end{pmatrix} \end{aligned}$$

The predicted behaviours of both outputs T_{op} and u_{ht} are computed with the new state equations. The disturbance models as well as the constraints are kept the same. The horizon is kept at 24 hours. The aim of the basic strategy is to apply a conditioning technique which consists in computing adequate temperature set-points to always keep the implemented PI controller at behaving in its linear band. The adapted optimisation problem is then formulated as expressed in (9). The current states x_b^k and x_i^k , the forecast disturbances $u_{DV}^{k:k+N-1|k}$ and the predicted state of occupancy $occ^{k+1:k+N|k}$ are given.

$$\begin{aligned} J &= \min_{T_{sp}^{k:k+N-1|k}} \mathcal{C}^T u_{ht}^{k:k+N-1|k} \\ \text{s.t. } x^{k|k} &= \begin{pmatrix} x_b^{k|k} & x_i^{k|k} \end{pmatrix}^T \\ \forall j \in k \dots k+N-1 & \\ x^{j+1|k} &= Ax^{j|k} + B_{DV} u_{DV}^{j|k} + B_{T_{sp}} T_{sp}^{j|k} \\ T_{op}^{j+1|k} &= (1 \ 0) (Cx^{j+1|k}) \\ u_{ht}^{j|k} &= (0 \ 1) (Cx^{j|k} + D_{T_{sp}} T_{sp}^{j|k}) \\ u_{ht_{\min}} &\leq u_{ht}^{j|k} \leq u_{ht_{\max}} \\ T_{op_{\min}} &\leq T_{op}^{j+1|k} \leq T_{op_{\max}} \quad \forall j \setminus occ^{j+1|k} \neq 0 \end{aligned} \quad (9)$$

where \mathcal{C} is the same constant weighting vector as in (5).

It can be noted that the optimal value J of the objective function in (9) is the same as the optimal value J in (5). Indeed, since the temperature set-point is not constrained and the weighting vector \mathcal{C} is the same in both cases, there always exists an optimal set-point T_{sp} which provides the same optimal power supplied u_{ht} in both formulations.

The resulting room temperature profile and power supplied by the MPC-PI controller implementing the basic strategy are depicted in figure 7. Performances of the controller will be discussed in section 5.

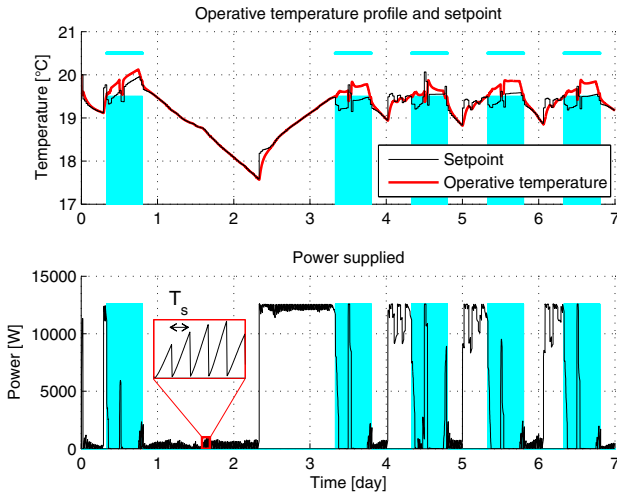


Fig. 7. Results of applied basic MPC-PI controller

From figure 7, it can be seen that undesired behaviours occur at the power limits. Quick power variations are obviously caused by the basic strategy and are explained as follows. In order to keep the PI controller into its linear band and not to violate the power constraints, the MPC controller computes the set-points such that the estimated power to be supplied is just at its limits *i.e.* $u_{ht}^k = u_{ht_{min}}$, when considering the zoomed illustration. But then, since the implemented PI controller works at a faster rate than the MPC-PI controller with $T_f \ll T_s$, meanwhile the next set-point computation, T_{op} converges towards T_{sp} thus increasing the error (from negative values to positive ones). Additional power is then supplied by the implemented PI controller accordingly. The effect is symmetrical whenever the higher power limit is targeted. Quick power variations are damaging to equipment when power limits are alternatively solicited at high frequencies.

4.4 Improved strategy

The undesired behaviours of the closed-loop system need to be taken into account in the MPC strategy to be eliminated. From the controller's point of view, the slow T_s sampling rate suggests that the estimated power u_{ht} computed by the basic strategy is kept constant during T_s . However, the power actually supplied by the implemented PI controller varies during this period of time.

To prevent these power variations at power limits, a second MPC strategy, called the improved strategy, is proposed. It consists in implementing and commuting between two operating modes. Its main operating mode is the basic strategy described above. Its subsidiary operating mode forces the implemented PI controller to maintain the power limit targeted by the main operating mode throughout T_s . A simple way to do that is to saturate the PI controller to the assigned power limit by providing adapted temperature set-points. This rule-based mechanism is described in expression (10).

$$\begin{aligned} & \text{if } u_{ht}^k > u_{ht_{min}} + \epsilon \text{ (resp. } u_{ht}^k < u_{ht_{max}} - \epsilon \text{)} \\ & \text{then } T_{sp}^k = T_{sp}^k - \xi \text{ (resp. } T_{sp}^k = T_{sp}^k + \xi \text{)} \end{aligned} \quad (10)$$

where $\epsilon \in \mathbb{R}$ and $\epsilon \geq 0$, and $\xi \in \mathbb{R}$ and $\xi \gg 0$. Typically, ϵ is chosen to be approximatively 10% of the power limit

and ξ is chosen big enough to ensure that the adapted set-point is not reached within T_s .

The resulting room temperature profile and power supplied by the MPC-PI controller implementing the improved strategy are depicted in figure 8. Performances of the controller will be discussed in section 5.

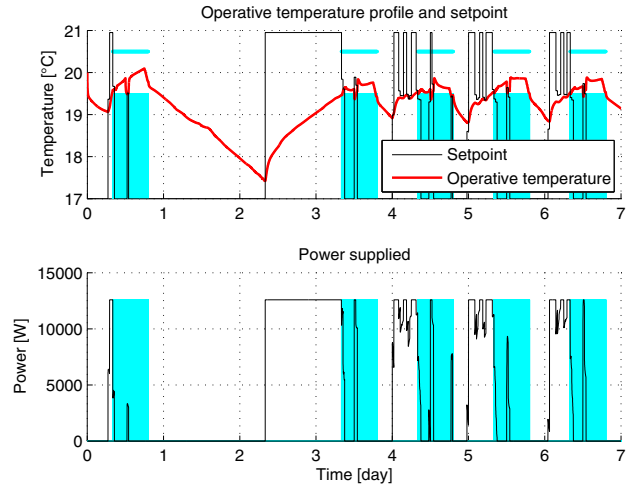


Fig. 8. Results of applied improved MPC-PI controller

5. COMPARISON OF THE CONTROLLERS PERFORMANCES

We define two criteria for the evaluation of the controllers performances. On one hand, the comfort measured by the percentage of time spent, during occupancy throughout the whole week, into the comfort zone expressed in (3). On the other hand, the energy measured by the total amount of energy consumed, throughout the whole week, via the power supplied to the heating equipment. Table 1 compares the performances of the three strategies, namely the benchmark, the basic and the improved strategies.

Controller	Comfort(%)	Energy(kWh)
Benchmark	87.3	647
MPC-PI.basic	94.6	656
MPC-PI.improved	93.4	651

Table 1. Performances of the controllers

Regarding the comfort performance, the benchmark strategy presents the least percentage of time spent in the comfort zone. Due to the low model sampling rate T_s , the benchmark strategy is unable to reject efficiently the fast varying disturbances. Whereas, with the same sampling rate T_s , the MPC-PI controller can rely on the integrated controller to reject efficiently these same disturbances. Hence, integrating a closed-loop model into the MPC-PI controller induces, to some extent, interesting robustness properties. Differences in the comfort performances between the improved and basic strategies are mainly caused by weekends where the room temperature falls during longer periods of time but at different rates. The prediction/control horizon allows the heating relaunch only 24 hours before occupancy. At relaunch, T_{op} equals to 17.6°C with the basic strategy, while T_{op} equals to 17.4°C with the improved strategy. With a horizon of 24 hours, the

limited heating power of the equipment is not enough for the improved strategy to compensate the temperature's drop. Table 2 illustrates the performances of the controllers when a longer horizon is provided.

Controller	Comfort(%)	Energy(kWh)	Relaunch(h)
Benchmark	87.8	650	27.4
MPC-PI.basic	94.8	657	26.9
MPC-PI.improved	94.4	654	27.9

Table 2. Performances of the controllers with a horizon of 30 hours

From table 2, it can be noted that the improved strategy is more impacted by a longer horizon than the other controllers. Moreover, for any controller, the heating relaunch is optimally triggered within the horizon of 30 hours. Therefore, providing longer horizons will have no effect on the controllers performances. On the other hand, providing shorter horizons will affect the controllers performances with the tendencies illustrated by table 1. Comparing tables 1 and 2, the chosen horizon of 24 hours is a reasonable compromise in terms of comfort versus energy performances as well as computational load criterion.

Regarding the energy performances, they are directly related to the comfort performances.

To sum up, the improved strategy presents better comfort performances than the benchmark strategy, thanks to efficient disturbance rejection, while eliminating undesired and damaging power variations caused by these rejections.

6. CONCLUSION

We have developed a supervisory MPC controller able to take into account existing integrated controllers, including power saturations and operating modes, without increasing the complexity of its strategy. We have implemented a PI controller with an anti-windup mechanism as the so-called integrated controller. The different behaviours of the PI controller caused by power saturations require the use of a hybrid model of the PI control which is complex to handle at the optimisation level. We proposed an MPC strategy which implement solely the linear model of the PI control while forcing the implemented PI controller to behave in this linear band. To avoid undesired power variations, caused by continuous temperature regulation, a single rule-based mechanism which consists in commuting between a dynamic main operating mode and a static subsidiary operating mode whenever power limits are targeted is implemented.

As a result, the complexity of the developed MPC controller is at most the same as MPC controllers driving directly equipment. Linear models are used even if the integrated controller presents hybrid behaviours. Integration of closed-loop models in the supervisory control introduces interesting robustness properties. Low process dynamic models as well as low calculation rates of the control input can be used for the supervisory control since it can rely on the high dynamic of the implemented PI controller to efficiently reject disturbances. Simple rule-based mechanisms, replacing complex hybrid solvers, easily eliminate

undesired behaviours. Compared to MPC controllers driving directly equipment, the developed strategy ensures, for longer periods of time, the occupants' thermal comfort.

Some future work can include the investigation of the reliability of estimated energy consumptions. This already available information can then be used in building energy management systems.

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