Investigating the abilities of various building in handling power sheddings

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***Abstract*—Nowadays, several insulation configurations exist in residential buildings, and during renovation works of these buildings, different investment can be considered. The contribution of this article is a method of evaluation of the ability of each configuration to remain within a comfort zone during load sheddings period. This question is of importance in the relationship, and then in the price setting, between the user (inhabitant of the house) and the energy provider who uses these load sheddings period to optimize his production on a national or regional scale.**

We proceed to the evaluation as follows: an optimization method is used to compute, in a dynamical context, the best heating strategy. The weather conditions and the comfort constraints define (through a dynamical optimization problem) the actual ability of the building to guarantee a satisfying comfort during load sheddings period independently of the regulation strategy.

I. Introduction

Nowadays significant efforts are made to reduce electricity peak demand. In Europe these peaks occur especially during winter time, and are thus due to a large extent to heating systems. In order to guarantee the grid's stability, studies are carried out on load reduction. This reduction can be achieved thanks to a careful housing design that can both capture and restore efficiently the solar gains [1]. An advanced heating control could be another solution. This control can be based on power tarification [2] and can use the building's thermal mass as an asset to shift the building's consumption, thus reducing the peak consumption [3], [4].

This article follows this approach by studying the load shedding opportunities on five thermal models from poorly to well insulated buildings. This article's contribution consists in an under constraints dynamic optimization method in continuous time allowing us to accurately compute optimal trajectories (when they exist) satisfying the constraints [5], [6], [7], [8]. By acting on the load shedding's duration, we can figure out the maximum duration of a complete heating load shedding capable of maintaining an acceptable level of comfort while shifting the consumption. The results obtained show that the thermal mass of a poorly insulated building is not sufficient to perform load sheddings superior to ten minutes. Thus, the use of buildings as power stocks only seems efficient in the case of sufficiently insulated buildings which can handle load sheddings of several hours.

II. Building Model

A. Building description

The building under study is a French single-family house. The actual building is an experimental passive house part of INCAS platform built in Bourget du Lac, France. For our study, five version low performance versions of the building are considered. The reference version corresponds to a house build before the first French thermal regulation. The four other versions corresponds to different renovations levels of the reference version. It is then possible to study the effects of renovation on the peak load management. The reference version has two floors for a total living floor area of 89 m^2. 34% of its south facade surface is glazed while the north facade has only two small windows. All the windows are simple glazed. The south facade is also equipped with solar protections for the summer period. The external walls are made with a 30 cm-thick layer of concrete blocks and the floor is composed of 20 cm reinforced concrete. There is no insulation in the building except for the 10 cm of glass-wool in the attic. According to thermal simulation results using Pléiades+COMFIE [9], the heating load is 253 kWh/(m^2.year) which is typical for such type of house. Comparisons had been performed during the design phase on the passive house version of this building with other simulation tools like Energy Plus and TRNSYS [10].

Fig. 1. 3D view of the house (west and south facades)

Four different renovations of this building are presented in Table I:

TABLE I
VERSIONS OF THE CONSIDERED BUILDINGS THROUGHOUT THE RENOVATIONS WORKS

Version	Renovation applied	Heating consumption (kWh/m^2.year)
Original (1)	none	253
Roof insulation (2)	(1)+ 30cm of glass-wool in the attic	246
Triple glazing (3)	(2)+Triple glazed windows	215
Insulation of external walls (4)	(3)+ 15cm of glass-wool for external walls	93
Heat recovery ventilation (HRV) (5)	(4)+HRV with an efficiency of 0.5	80

B. Thermal model

The thermal modeling of the building is made by dividing it in zones of homogenous temperature. For each zone, each wall is then divided in meshes small enough to have also a homogeneous temperature. There is one more mesh for the air and furniture of the zone. Eventually, a thermal balance is done on each mesh within the building. The thermal balance takes into account:

- P_{cond}: the loss (or gain) by conduction in walls, floor and ceiling.
- P_{sol}: the gain due to solar irradiance through the windows
- P_{conv}: the loss (or gain) due to convection at walls surface
- P_{in}: the internal gain due to heating, occupancy and other loads (only for zone air mesh)
- P_{bridges}: heat losses through thermal bridges, no associated for thermal mass
- P_{ventil} : heat loss due to air exchange

If applied to the mesh corresponding to the air of the zone, the thermal balance equation is:

$$C_{\text{air}}\dot{T}_{\text{air}} = P_{\text{in}} + P_{\text{cond}} + P_{\text{bridges}} + P_{\text{ventil}} + P_{\text{sol}} + P_{\text{conv}} \quad (1)$$

with the thermal capacity of the node air (including furniture) and the temperature of the mesh. The equation (1) is repeated for each mesh of each zone to obtain the following matrix system [10]:

$$\begin{aligned} C\dot{T}(t) &= AT(t) + EU(t) \\ Y(t) &= JT(t) + GU(t) \end{aligned}$$

with:

- T mesh temperatures vector
- U driving forces vector (climate parameters, heating, etc.)
- Y outputs vector (here, temperature of the air nodes)
- C thermal capacity diagonal matrix
- A, E, J, G matrix linking every previous matrix

In order to simulate such a model, it is important to know the occupancy of the building, which defines partly P_{in} with the emission of heat by the inhabitants and the appliances. The second part of heat emission in P_{in} is due to the heating system. Another important aspect is the weather model. It defines the loss due to heat transfer with the ambient temperature and the gain with solar irradiance. All the data of the occupancy and weather models are contained in the driving forces vector U.

III. MODEL AND CONSTRAINTS

A. Model reduction

A high order linear model is now available. But in a optimization purpose its state dimension is too big to allow a fast convergence of the optimization algorithm. Thus a reduction method is used to reduce this state dimension and to make the algorithm faster. To reduce this dimension, several methods exist such as singular perturbations [11], or identification methods [12]. But in this case, an efficient method is the balanced truncation [13]. Indeed, this truncation consists in removing the state variables which receive the less energy from the input and give the less energy to the output. That is to say, the state variables that are easily negligible from an energetic view-point. Now, to determine the order of the reduced model, we compare the error between the high order model and the reduced ones over one year in terms of mean and standard deviation and we take the minimal order such that these statistical properties are both inferior to 0.1. In our case all models are at least third orders, and one of them is a fourth order one.
On table II, one can find the different time constants of the considered models. It is noticeable that the main effect of the renovation works bears on the slow time constant, particularly the adjunction of insulation. Moreover, one can also see that a thermal building model is clearly a three separated time scales model [11].

TABLE II
VALUE OF THE TIME CONSTANTS OF THE FIVE DIFFERENT MODELS.

	1$^{\text{st}}$	2$^{\text{nd}}$	3$^{\text{rd}}$	4$^{\text{th}}$	5$^{\text{th}}$
Time constants	8min. 13h. 95h.	7min. 13h. 98h.	8min. 2h. 8h. 91h.	9min. 24h. 180h.	9min. 15h. 170h.

B. Model and constraints

1) Model notations: In the following, we use the classical linear state space representation to represent the model:

$$\dot{x}(t) = Ax(t) + Bu(t) + d(t) \quad (2)$$
$$y(t) = Cx(t) \quad (3)$$

where x is the state of the model, y is the inside temperature, d represents the influence of the outside temperature and the solar fluxes on the heating of the house and u represents the heating flux on the air node and is the control variable.

2) Constraints:

a) Inside temperature constraints: The temperature constraints are 24 hours periodic and are:

- $y \leq 24°C$
- $y \geq 14°C$ between 9 a.m. and 5 p.m.
- $y \geq 20°C$ otherwise.

To simplify the notations for the algorithm, we write the temperature constraints as follows:

$$y^- \leq y \leq y^+ \tag{4}$$

b) Control constraints: The control constraints are not the same for all systems:

- $0 \leq u \leq 20$ kW for the buildings whose walls have not been insulated.
- $0 \leq u \leq 10$ kW for the buildings whose walls are insulated.

To simplify the notations for the algorithm, we write the control constraints as follows:

$$0 \leq u \leq u^+ \tag{5}$$

c) Load shedding: The load sheddings consist in daily time period where the heating of the house is not allowed to consume any energy. In our case the load sheddings are 24 hours periodic and start everyday at 5 pm. The objective of the paper is to know the maximum duration of these load sheddings such that it becomes impossible to satisfy both (4) and (5).

IV. Method and algorithm

A. Method

In order to characterize the duration of load shedding which allows the inside temperature to satisfy (4) while the heating power satisfies (5), a state constrained optimal control approach is used. Indeed, setting (4) and (5) as constraints allows us to quantify (from an intrinsic view-point) the maximum load shedding duration feasible without degradation of the comfort. Indeed, when there exists no solution for the constrained optimal control problem, we know that the load sheddings are too long and this does not depend on the regulation system but only on the capacity of the building to store energy.

To know the maximum duration of the load shedding, the procedure consists in solving a sequence of optimal control problems with load shedding period getting longer and longer until there exists no solution satisfying the constraints (4) and (5).

B. Algorithm

For this problem, the constraints are (4) and (5) and the considered criterion is the energy consumed over the whole week. To solve the state constraint optimal control problem a maximum principle-based interior method is used [5], [14], [6], [7], [8], which has been adapted for the energy consumption problem. The criterion is given by the following:

$$J = \min_{u \in [0,u^+]} \int_0^T u(t)dt \tag{6}$$

with the dynamics and the state constraint $y \in [y^-, y^+]$ seen above, and where $T = 7$ days.

The first step, in this algorithm is to operate the following change in variable on the control variable u:

$$u \triangleq \phi(\nu) = u^+ \left(\frac{e^{k\nu}}{1 + e^{k\nu}} \right) \tag{7}$$

This change in variable is such that $\phi : \mathbb{R} \mapsto (0, u^+)$, thus ν is an unconstrained variable and the optimization problem is now:

$$J = \min_{\nu \in \mathbb{R}} \int_0^T \phi(\nu)dt \tag{8}$$

To solve this problem, an indirect method using an adjoint vector p is used. This adjoint vector p has the same dimension than the state x of the reduced dynamical system (2) and is such that:

$$\frac{dp}{dt}(t) = -A^t p(t) - C^t \gamma_y'(Cx(t)) \tag{9}$$

where γ_y' is the derivative of the following function

$$\gamma_y(y(t)) = \left(\frac{y^+(t) - y^-(t)}{\sqrt{(y^+(t) - y(t))(y(t) - y^-(t))}} - 1 \right)^{2.1} \tag{10}$$

Now, to compute the optimal control, an interior method is used. It consists in solving a sequence of optimal control problem, depending on a parameter ϵ_n, converging to the optimal solution of the problem. The iterative algorithm is the following:

- Step 1: Initialize the functions $x(t)$ and $p(t)$ such that the initial $Cx(t) \in (y^-(t), y^+(t))$ for all $t \in [0, T]$, and set $\epsilon = \epsilon_0$. Note that $x(t)$ and $p(t)$ do not need to satisfy any differential equations at this stage, even if it is better if they do. Often, p can be chosen identically equal to zero at first step.
- Step 2: Compute $\nu_\epsilon^* = \sinh^{-1}\left(-\frac{1+p^t B}{\epsilon}\right)$. Thus the optimal solution $u_\epsilon^* = \phi^{-1}(\nu_\epsilon^*)$ is given using equation (7) with $k = 0.8$.
- Step 3: Solve the 2 differential systems of equation $\frac{dx}{dt} = Ax + Bu_\epsilon^*$ and $\frac{dp}{dt} = -A^t p - C^t \gamma_y'(Cx)$ forming a two point boundary values problem using bvp4c (see [15]), with the following boundary constraints $x(0) = x_0$ and $p(T) = 0$.
- Step 4: Decrease ϵ, initialize $x(t)$ and $p(t)$ with the solutions found at Step 3 and restart at Step 2.

In our case, the sequence (ϵ_n) has been chosen such that $\epsilon_n = 10^{-\frac{n}{10}}$ with $n = 0 \cdots 40$. The proof of convergence of this algorithm can be found in [8].

V. Results

The considered optimization takes place in winter over one week where the outside temperature is given on Figure 2. On Figures 3 and 4, one can see the influence of the load sheddings on the inside temperature of the buildings.

A. Summary of the results

The behavior of the five systems described in Table I are as follows:

- **First Building:** The maximum duration of daily load shedding is of **10 minutes**. These daily load sheddings induce an increasing of 11% of the consumed energy over one week compared to the optimization of this building without load shedding (1527 kWh without load sheddings and 1688 kWh with daily 10 minutes load sheddings). Moreover, one can see that it is impossible to store a sufficient amount of energy in this building within 24 hours to allow the building to be comfortable and to bear load sheddings longer than 10 minutes.
- **Second Building:** The maximum duration of daily load shedding is of **20 minutes**. These daily load sheddings induce an increasing of 18% of the consumed energy over one week compared to the optimization of this building without load shedding (1514 kWh without load sheddings and 1778 kWh with daily 20 minutes load sheddings). Moreover, one can see that it is impossible to store a sufficient amount of energy in this building within 24 hours to allow the building to be comfortable and to bear load sheddings longer than 20 minutes.
- **Third Building:** The maximum duration of daily load shedding is of **20 minutes**. These daily load sheddings induce an increasing of 20% of the consumed energy over one week compared to the optimization of this building without load shedding (1163 kWh without load sheddings and 1390 kWh with daily 20 minutes load sheddings). Moreover, one can see that it is impossible to store a sufficient amount of energy in this building within 24 hours to allow the building to be comfortable and to bear load sheddings longer than 20 minutes. But, the adjunction of this triple glazing induces a global reduction of the consumed energy of 30%.
- **Fourth Building:** This configuration can handle daily load sheddings of duration superior to **5 hours**. These daily load sheddings induce an increasing of 16% of the consumed energy over one week compared to the optimization of this building without load shedding (555 kWh without load sheddings and 641 kWh with daily 5 hours load sheddings). Moreover, one can see that this configuration allows the building to handle long daily load sheddings without a strong degradation of the comfort. Here, the increasing of the insulation induces a global reduction of the consumed energy of 50% compared to the configuration of the third building.
- **Fifth Building:** This configuration can handle daily load sheddings of duration superior to **5 hours**. These daily load sheddings induce an increasing of 17% of the consumed energy over one week compared to the optimization of this building without load shedding (526 kWh without load sheddings and 617 kWh with daily 5 hours load sheddings). Moreover, one can see that this configuration allows the building to handle long daily load sheddings without a strong degradation of the comfort. Here, the fifth building induces a global reduction of the consumed energy of 5% compared to the fourth building.

Moreover, one can see on Figure 3 the inside temperature of each system with their respective maximum daily load sheddings duration. Plus, on Figure 4, one can see precisely the last load shedding response of the week.

B. Explanation of the results

As, seen on table II, one can see that the influence of the renovation works mainly bears on the slow time constant of the systems. It is particularly noticeable that once some insulation has been added to the building, the load sheddings last for several hours and the slow time constant is twice bigger than the one of the non insulated models. Thus, the renovated buildings tend to be slower than the original building. But, the slow time constant does not explain totally the global behavior of the system towards load sheddings. Indeed, as one can see on Table III the renovations works on the building make, for both medium and slow time scales the pole and the zero move away from each other. As a consequence, the slow time scales of the renovated system are more controllable than the slow time scales of the original building. This increasing of the controllability of the system's slow scale, actually means that less time is needed to store energy using the inertia of the building and not only the inertia of the air. As a consequence, it is possible to store efficiently energy within 24 hours and then remain comfortable even when long (but predicted) load shedding periods occur. The lack of controllability of the slow time scales in the original building means that it is impossible to store energy using the building's inertia within 24 hours no matter the energy management system. Then, even if these buildings represent an important consumption of energy, they are not the most appropriate to demand response strategy on their heating load, due to the impossibility to use the envelope as an efficient thermal storage.

TABLE III

VALUE OF THE POLES AND THE ZEROS OF THE DIFFERENT TIME SCALES FOR THE FIRST AND THE FIFTH BUILDING.

	1^{st} building	5^{th} building
slow pole	$P = -0.0105$	$P = -0.00588$
slow zero	$Z = -0.0178$	$Z = -0.0193$
medium pole	$P = -0.0789$	$P = -0.0669$
medium zero	$Z = -0.268$	$Z = -0.277$

VI. CONCLUSION

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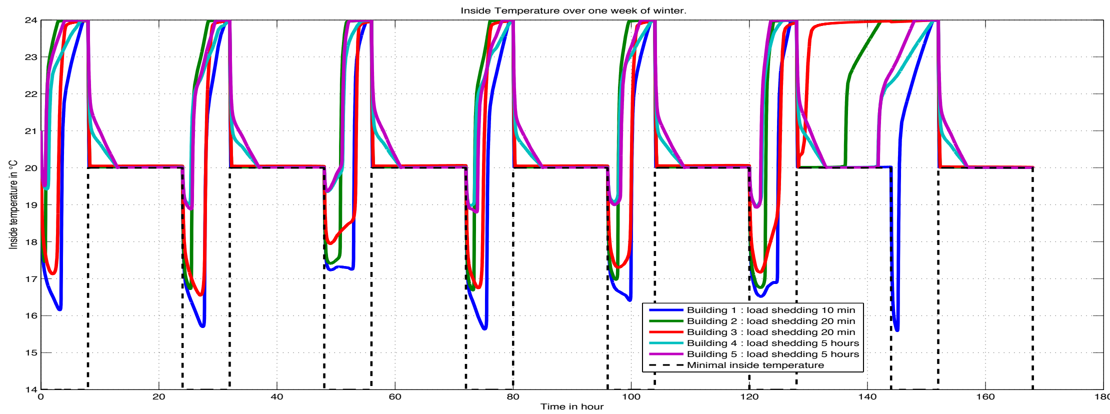

Fig. 3. Comparison of the optimal inside temperature of each building with the maximum bearable load sheddings duration

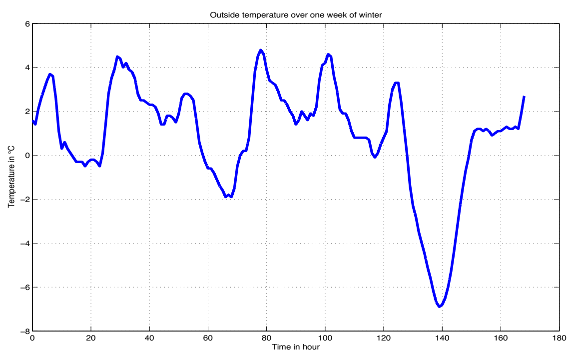

Fig. 2. External temperature over two weeks of winter

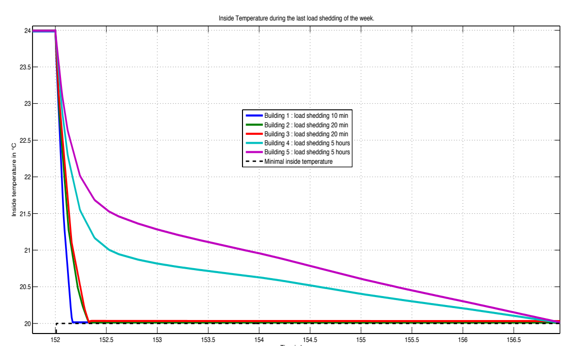

Fig. 4. Comparison of the optimal inside temperature during the load shedding of the last day of the week

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