Robust Provision of Frequency Reserves
by Office Building Aggregations ⋆

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Abstract: Active participation of demand-side resources in power system control tasks, i.e., demand response, is expected to facilitate the integration of renewable energy sources in the grid. In this paper, we present a novel hierarchical control scheme to enable provision of frequency control reserves by a pool of office buildings managed by an aggregator. The reserves are provided by controlling the consumption of the heating, ventilation, and air conditioning (HVAC) systems in a robust way. The aggregator determines once a day the optimal amount of reserves and its allocation among the participants. On the building level, a robust MPC controller optimizes the HVAC system consumption every 15 minutes, and a proportional controller provides the reserves in real-time. We demonstrate the performance of the proposed scheme in simulations considering different buildings and reserve product characteristics. The results show that office building aggregations can provide large amounts of frequency reserves in a robust way, while satisfying occupants' comfort and respecting privacy.

1. INTRODUCTION

The increasing penetration of fluctuating renewable energy sources (RES) in the electricity grid calls for more frequency reserves, which traditionally come from conventional generators, see e.g., Makarov et al. [2009]. Recently, there is a rising interest in also engaging demand-side resources in power system services, which is commonly referred to as demand response (DR). If properly aggregated and controlled, loads may be able to provide frequency reserves more effectively, at a lower cost, and/or with less environmental impact, see e.g., Callaway and Hiskens [2011]. Office buildings are good candidates for reserve provision because substantial parts of the consumption of their heating, ventilation, and air conditioning (HVAC) systems can be shifted in time due to their large thermal inertia. In addition, office buildings typically consume large amounts of power; therefore, even small aggregations could participate in the reserve market.

The type of services that can be offered to the power system from office buildings highly depends on the building type and HVAC system, see Motegi et al. [2007], Oldewurtel et al. [2013]. So far, most of the work has focused on peak shedding, load shifting, or cost minimization applications. For example, Braun [1990] uses an optimization-based algorithm and Oldewurtel et al. [2010] a model predictive controller (MPC) for reduction of a building's peak consumption. Ma et al. [2012], Vrettos et al. [2013a] proposed MPC schemes for electricity bill minimization employing predictions of future evolution of electricity costs, building occupancy, weather conditions, and/or local RES production. Frequency support by buildings with variable air volume (VAV) systems was investigated in Hao et al. [2012, 2013], by controlling the fan speed to track a regulation signal.

The aforementioned literature focuses exclusively on DR with individual buildings. Recently, methods to allow aggregations of residential thermostatically controlled loads (TCLs) to participate in reserve markets have been proposed, e.g., in Callaway and Hiskens [2011], Vrettos et al. [2012], Mathieu et al. [2013], Vrettos and Andersson [2013]. However, aggregating office buildings to provide power system services is only marginally investigated. In Vrettos et al. [2013b], we have recently shown how the HVAC systems of office building aggregations can be controlled to jointly mitigate schedule deviations for balance groups (BGs).

In this paper, we propose a novel three-level hierarchical control scheme to enable participation of office building aggregations, managed by an aggregator, in frequency control. In the first level (Lv1), the aggregator determines on a daily basis the optimal amount of reserves and their allocation among the participants. The second level of the algorithm (Lv2) takes place every 15 minutes locally at each building. A robust MPC controller determines the consumption set-points of the HVAC system that minimize electricity costs, while ensuring provision of reserves. The third level (Lv3) is a proportional controller that tracks the frequency control signal communicated by the transmission system operator (TSO) by shifting the HVAC consumption around the scheduled value calculated by Lv2.

An important contribution of our work is that the reserve determination, allocation, and provision are robust against the frequency control signal sent by the TSO, which is uncertain when the decisions are made. With the proposed approach, no assumptions on the bandwidth of the signal are needed, as in Hao et al. [2012, 2013]. In addition, the decentralized nature of Lv2 respects occupants' privacy and keeps the communication costs at a minimum. Another contribution is an analysis of the effect of reserve characteristics (e.g., capacity payment, and bid duration and symmetry) on the amount of reserves that can be extracted from energy constrained resources, such as buildings.

The remainder of the paper is organized as follows. In Section 2, we introduce the characteristics of frequency control, the notation, and the modeling work. In Section 3, we describe the proposed hierarchical control scheme, with a particular focus on the robust design. The investigation setup is explained in Section 4, and simulation results are presented in Section 5. In Section 6, we investigate the effect of different reserve characteristics, whereas insights and recommendations are provided in Section 7. Section 8 concludes our work.

2. PRELIMINARIES

2.1 Load Frequency Control

Typically, the TSO controls power system frequency in three steps: primary, secondary and tertiary control. Primary control stabilizes frequency after a disturbance has occurred, secondary control restores the frequency to its nominal value and maintains the desired exchanges between different control areas, and tertiary control releases secondary control in case of large disturbances. We focus on secondary frequency control, which is commonly referred to as automatic generation control (AGC), load frequency control (LFC), or regulation. In this paper, we adopt the name LFC.

The provision of LFC reserves is subject to different regulations in different countries. In this paper, we focus on the Swiss power system, see Swissgrid [2013a]. In Switzerland, and many other European countries, LFC reserves are procured by generators in a market setting. The providers bid their reserve capacity and price in weekly pay-as-bid auctions. Only bids with a minimum capacity of 5 MW and a symmetrical control band are allowed. In real-time, the LFC reserves are automatically requested from the generators via a signal sent by the TSO, typically every four seconds. The reserve requests are proportional to each bidder's contracted capacity. The reserve capacity is remunerated at the accepted bid price, whereas the reserve energy payment is coupled with the spot market price.

2.2 Modeling

The building models considered in this paper are based on HVAC systems 1 and 5 from Oldewurtel [2011], which are called systems A and B hereafter. System A includes radiators for heating and cooled ceilings for cooling. In system B, both heating and cooling are performed using thermally activated building systems (TABS). Both systems control also the blinds' position and lighting. Different to Oldewurtel [2011], free cooling is neglected since it consumes no electric power, and mechanical ventilation is not considered for system B because changing the fresh air flow rate for DR purposes would have immediate (adverse) effects on the occupants. Both building systems can be described by linear state space models as

$$x_{t+1}^b = A^b x_t^b + B_t^b u_t^b + E^b v_t^b + R^b \Delta u_t^b , \qquad (1)$$

$$y_t^b = C^b x_t^b + D_t^b u_t^b + F^b v_t^b , \qquad (2)$$

where $b \in \{1,...,L\}$ is the building index, $x_t^b \in \mathbb{R}^{n_x}$, $n_x = 12$, denotes the states at time step t, reflecting the temperatures in the walls, floor, and ceiling; $y_t^b \in \mathbb{R}^{n_y}$, $n_y = 2$, denotes the outputs, i.e., the room temperature and illuminance; $u_t^b \in \mathbb{R}^{n_u}$, $n_u = 4$, denotes the HVAC system control inputs, as described above; $v_t^b \in \mathbb{R}^{n_v}$, $n_v = 3$, denotes the external disturbances, given as outside temperature, solar radiation, and internal gains; and $\Delta u_t^b \in \mathbb{R}^{n_r}$ denotes the change in consumption due to reserve provision, which represents the uncertainty in our model. In this paper, the external disturbances are assumed known, i.e., perfectly predicted. Note that the matrices B_t^b and D_t^b are time-varying. This is due to the bilinear dependence of blind position and solar radiation, which becomes linear, time-varying if the solar radiation is known.

We assume that each building provides the reserve by controlling a single heating/cooling actuator, i.e., $n_r = 1$. In this case, the matrix R^b consists of the columns of B_t^b that correspond to this actuator. The TSO reserve requests are proportional to buildings' capacities based on a normalized LFC signal $w_t \in [-1, 1]$, see Swissgrid [2013a]. Therefore, the change in HVAC system consumption can be parametrized as

$$\Delta u_t^b = w_t r_t^b , \qquad (3)$$

where r_t^b denotes the reserve capacity of building b at time step t. The signal w_t is uncertain, and so is the change in consumption Δu_t^b. Extension to multiple actuators is straightforward for the scheduling problem of Lv1, but more involved for the building control problems of Lv2 and Lv3.

Denote with $x_{t+k|t}^b \in \mathbb{R}^{n_x}$ the predicted state of building b for time $t + k$ at time t. The predicted states at time t along a prediction horizon N are assembled in one vector as $\mathbf{x}_t^b = [x_{t|t}^b \ x_{t+k|t}^b \cdots x_{t+N|t}^b]^T \in \mathbb{R}^{n_x(N+1)}$. Adopting the same notation for inputs and disturbances ($\mathbf{u}_t^b \in \mathbb{R}^{n_u N}$, $\boldsymbol{\Delta u}_t^b \in \mathbb{R}^{n_r N}$, $\mathbf{v}_t^b \in \mathbb{R}^{n_v N}$), the building dynamics along N can be written as

$$\mathbf{x}_t^b = \mathbf{A}^b x_0^b + \mathbf{B}_t^b \mathbf{u}_t^b + \mathbf{E}^b \mathbf{v}_t^b + \mathbf{R}^b \boldsymbol{\Delta u}_t^b , \qquad (4)$$

$$\mathbf{y}_t^b = \mathbf{C}^b \mathbf{x}_t^b + \mathbf{D}_t^b \mathbf{u}_t^b + \mathbf{F}^b \mathbf{v}_t^b , \qquad (5)$$

where the matrices $\mathbf{A}^b, \mathbf{B}_t^b, \mathbf{E}^b, \mathbf{R}^b, \mathbf{C}^b, \mathbf{D}_t^b$, and $\mathbf{F}^b$ are of appropriate dimensions. The constraints on outputs (comfort zone) and HVAC inputs along N can be expressed as

$$\mathbf{y}_{min}^b \le \mathbf{y}_t^b \le \mathbf{y}_{max}^b , \qquad (6)$$

$$\mathbf{u}_{min}^b \le \mathbf{u}_t^b + \mathbf{H}^b \boldsymbol{\Delta u}_t^b \le \mathbf{u}_{max}^b , \qquad (7)$$

where $\mathbf{H}^b \in \mathbb{R}^{n_u \times n_r}$ is a matrix with entries 0 or 1. By substituting (4) and (5) in (6) and rearranging, the constraints can be expressed using only the control inputs and the uncertainty as

$$\mathbf{G}^b \mathbf{u}_t^b + \mathbf{S}^b \boldsymbol{\Delta u}_t^b \le \mathbf{Q}^b , \qquad (8)$$

where the matrices $\mathbf{G}^b, \mathbf{S}^b$, and $\mathbf{Q}^b$ are defined as

$$\mathbf{G}^b = \begin{bmatrix} \mathbf{G}_p^b \\ \mathbf{I} \\ -\mathbf{G}_p^b \\ -\mathbf{I} \end{bmatrix}, \mathbf{S}^b = \begin{bmatrix} \mathbf{S}_p^b \\ \mathbf{H}^b \\ -\mathbf{S}_p^b \\ -\mathbf{H}^b \end{bmatrix}, \mathbf{Q}^b = \begin{bmatrix} -\mathbf{Q}_p^b + \mathbf{y}_{max}^b \\ \mathbf{u}_{max}^b \\ \mathbf{Q}_p^b - \mathbf{y}_{min}^b \\ -\mathbf{u}_{min}^b \end{bmatrix}, \quad (9)$$

$$\mathbf{G}_p^b = \mathbf{C}^b \mathbf{B}_t^b + \mathbf{D}_t^b , \ \mathbf{S}_p^b = \mathbf{C}^b \mathbf{R}^b , \qquad (10)$$

$$\mathbf{Q}_p^b = \mathbf{C}^b(\mathbf{A}^b x_0^b + \mathbf{E}^b \mathbf{v}_t^b) + \mathbf{F}^b \mathbf{v}_t^b . \qquad (11)$$

Consider an aggregation of L buildings, i.e., $b = \{1 \ldots L\}$. The vector containing all predicted states of all buildings along N is denoted as $\mathbf{x}_t = [\mathbf{x}_t^1 \ \mathbf{x}_t^2 \ ... \ \mathbf{x}_t^L]^T \in \mathbb{R}^{n_x L(N+1)}$. Using the same notation for inputs and disturbances ($\mathbf{u}_t \in \mathbb{R}^{n_u LN}$, $\boldsymbol{\Delta u}_t \in \mathbb{R}^{n_r LN}$, $\mathbf{v}_t \in \mathbb{R}^{n_v LN}$) and stacking (8) for all buildings, the input and output constraints of the aggregation can be written in compact form as

$$\mathbf{G} \mathbf{u}_t + \mathbf{S} \boldsymbol{\Delta u}_t \le \mathbf{Q} , \qquad (12)$$

where $\mathbf{G}, \mathbf{S}$, and $\mathbf{Q}$ are block diagonal matrices with $\mathbf{G}^b, \mathbf{S}^b$, and $\mathbf{Q}^b$ on the diagonal, respectively.

3. CONTROLLER DESIGN

An overview of the hierarchical controller design is given in Figure 1. Lv1, the *Aggregator Scheduling*, takes place on a
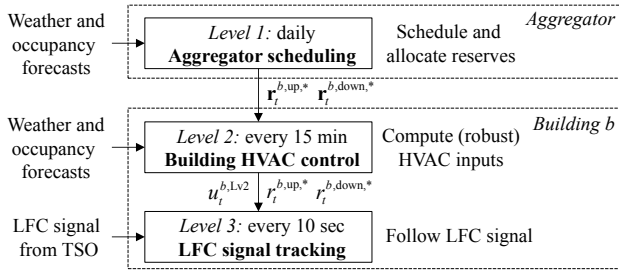
Fig. 1. Overview of the hierarchical controller: task sequence and information flow.

daily basis, and is carried out centrally by the aggregator. The goal is to determine the optimal reserve capacity and its allocation among the buildings. The optimal solution achieves the best tradeoff between profits from reserve provision and additional electricity costs due to increased energy consumption. In addition, the scheduling should guarantee comfort in case the reserve is called. The aggregator solves this problem using measurements of the current state of each building, given prices of electricity and reserves, as well as predictions of weather and occupancy for each building. Lv2, the *Building HVAC control*, takes place every 15 minutes and is carried out locally at each building. The goal is to determine the HVAC control inputs that minimize electricity costs, while ensuring that the scheduled amount of reserves can be provided respecting comfort. This is achieved by solving a robust MPC problem using the current measurements of the building, electricity and reserve costs, and predictions of weather and occupancy. Lv3, the *LFC signal tracking*, takes place in real-time, e.g., every 10 seconds, locally at each building. This is a proportional controller to track the requested LFC signal by controlling the power consumption.

3.1 Lv1: Aggregator Scheduling

The aggregator determines the optimal amount and allocation of reserves by solving a robust optimization problem over a prediction horizon N_1. The problem can be formulated as

$$(\mathbf{u}_t^*, \mathbf{r}_t^{\text{up},*}, \mathbf{r}_t^{\text{down},*}) :=$$

$$\arg\min \mathbf{c}_t^T \mathbf{u}_t - \frac{1}{2}\mathbf{k}_t^T(\mathbf{r}_t^{\text{up}} + \mathbf{r}_t^{\text{down}}) \tag{13}$$

$$\text{s.t.} \max_{-\mathbf{r}_t^{\text{down}} \leq \boldsymbol{\Delta u}_t \leq \mathbf{r}_t^{\text{up}}} [\mathbf{G}\mathbf{u}_t + \mathbf{S}\boldsymbol{\Delta u}_t \leq \mathbf{Q}] \tag{14}$$

$$\mathbf{M}\begin{bmatrix} \mathbf{r}_t^{\text{up}} \\ \mathbf{r}_t^{\text{down}} \end{bmatrix} = \mathbf{0}, \ \mathbf{r}_t^{\text{down}}, \mathbf{r}_t^{\text{up}} \geq \mathbf{0}, \tag{15}$$

where $\mathbf{c}_t$ and $\mathbf{k}_t$ denote the electricity cost and reserve capacity payment vectors, respectively; $\mathbf{r}_t^{\text{up}}, \mathbf{r}_t^{\text{down}} \in \mathbb{R}^{n_r L N_1}$ denote the vectors of up- and down-reserve capacities, respectively, for all buildings and for each predicted time step. Note that the formulation allows for different up- and down-reserves. By appropriately selecting $\mathbf{M}$, we can enforce symmetric reserves, and/or constant reserves over a given period of time. Also, note that (13) does not consider reserve energy payments. Including them in the formulation would introduce additional uncertainty because they are coupled to the spot price, which is unknown. The uncertainty $\boldsymbol{\Delta u}_t$ lies in a box determined by $\mathbf{r}_t^{\text{up}}$ and $\mathbf{r}_t^{\text{down}}$, which are optimization variables. Recall that the matrix $\mathbf{S}$ in (14) has the same structure as $\mathbf{S}^b$ in (9), i.e., $\mathbf{S} = [\mathbf{S}_p \ -\mathbf{S}_p]^T$. To obtain a robust counterpart problem, we substitute the uncertain constraint (14) with the deterministic constraint

$$\mathbf{G}\mathbf{u}_t + \begin{bmatrix} |\mathbf{S}_p|_\star & \mathbf{0} \\ \mathbf{0} & |-\mathbf{S}_p|_\star \end{bmatrix} \begin{bmatrix} \mathbf{r}_t^{\text{up}} \\ \mathbf{r}_t^{\text{down}} \end{bmatrix} \leq \mathbf{Q}, \tag{16}$$

where $|\cdot|_\star$ denotes the element wise absolute value operator. The outputs of this optimization problem are $\mathbf{u}_t^*$, $\mathbf{r}_t^{\text{up},*}$, and $\mathbf{r}_t^{\text{down},*}$ denoting the day-ahead optimal HVAC and reserve schedules for all buildings. The aggregator communicates $\mathbf{r}_t^{\text{up},*}$ and $\mathbf{r}_t^{\text{down},*}$ once a day to all buildings.

3.2 Lv2: Building HVAC Control

Every 15 minutes, the optimal HVAC control inputs are calculated by solving a robust MPC problem over a prediction horizon N_2, given the optimal reserve allocation from Lv1. The problem can be formulated as

$$\mathbf{u}_t^{b,*} := \arg\min \ (\mathbf{c}_t^b)^T \mathbf{u}_t^b \tag{17}$$

$$\text{s.t.} \max_{-\mathbf{r}_t^{b,\text{down},*} \leq \boldsymbol{\Delta u}_t^b \leq \mathbf{r}_t^{b,\text{up},*}} \left[\mathbf{G}^b \mathbf{u}_t^b + \mathbf{S}^b \boldsymbol{\Delta u}_t^b \leq \mathbf{Q}^b \right], \tag{18}$$

where $\mathbf{c}_t^b$ denotes the electricity cost vector for building b. The uncertainty $\boldsymbol{\Delta u}_t^b$ lies again in a box, but now its bounds are fixed from Lv1. We focus on MPC with open-loop predictions, i.e., the optimization is performed explicitly over the control inputs $\mathbf{u}_t^b$. For this case, we follow standard procedures from the literature, e.g., Ben-Tal and Nemirovski [1999], Löfberg [2012], to remove the uncertainty and derive the robust counterpart, which yields a linear program. Note that robust MPC with closed-loop predictions, where the optimization is performed over affine policies of the uncertainty, would also result in a linear program, yet with a larger number of variables. Preliminary simulations showed minor, or even zero, improvement with closed-loop predictions for this problem; therefore, MPC with open-loop predictions is used in this paper. The first input of the optimal control sequence determines the Lv2 set-point of the HVAC system for the next 15 minutes, i.e., $u_t^{b,\text{Lv2}} = \mathbf{u}_t^{b,*}(1)$.

3.3 Lv3: LFC Signal Tracking

In Lv3, the HVAC consumption is controlled around $u_t^{b,\text{Lv2}}$ to provide the requested frequency reserve. In practice, this can be achieved by controlling the heating/cooling device (e.g., heat pump) via a proportional or proportional-integral (PI) controller. The controller's reference signal is calculated by superimposing the incoming LFC signal on $u_t^{b,\text{Lv2}}$

$$u_t^{b,\text{Lv3}} = u_t^{b,\text{Lv2}} + \Delta u_t^b = u_t^{b,\text{Lv2}} + w_t r_t^{b,*}, \tag{19}$$

$$r_t^{b,*} = \begin{cases} r_t^{b,\text{up},*} & \text{if } w_t \leq 0, \\ r_t^{b,\text{down},*} & \text{if } w_t > 0 \end{cases}, \tag{20}$$

where $r_t^{b,\text{up},*}$ and $r_t^{b,\text{down},*}$ come from Lv1, and w_t is the normalized LFC signal. In this paper, we neglect the device-dependent dynamics and constraints, e.g., ramping rates, minimum down-time and/or run-time, and latencies; therefore, the LFC signal can be tracked perfectly provided that the comfort zone and input constraints are satisfied.

4. INVESTIGATION SETUP

To investigate the performance of the proposed method, we assume an aggregation of typical Swiss office buildings (system A and system B) participating in the reserve market. We differentiate between high or low window area fractions, heavy or light building envelopes, and high or low internal gains, which leads to a final number of sixteen building configurations. More information regarding the buildings can be found in Oldewurtel [2011]. Simulations were performed using the LFC signal from the Swiss control area in 2012. As a base case, we assume

that symmetric reserve bids with daily duration are allowed. Furthermore, the remuneration for reserve capacity is fixed at a price 10% higher than the retail electricity price, i.e., $k = 1.1c$. The temperature comfort zone during working hours is set to $[21, 24]^o$C for winter and to $[22, 25]^o$C for summer. During non-working hours and weekends these constraints are relaxed to $[12, 35]^o$C. The optimizations are performed with a time step of 15 minutes, and the prediction horizons are fixed to $N_1 = 48$ hours and $N_2 = 24$ hours.

With this setup, we perform a number of investigations. First, we run simulations for typical weeks in winter and summer. For each case, we show the optimal reserve amount, its allocation among buildings, and the operation of a building's HVAC system based on Lv2 and Lv3. For this analysis, we focus on a building with system A, high window area fraction, heavy envelope, and high internal gains, which we denote with A1 hereafter. Second, we perform a sensitivity analysis with respect to capacity payment, duration, and symmetry of bids. The purpose of this investigation is to understand the effect of the product structure on the amount of reserves that can be extracted. We also quantify the value of aggregating buildings to participate in the reserve market.

5. CONTROLLER PERFORMANCE

5.1 Winter Week

Figure 2 shows the consumption of the HVAC systems and the optimal reserve capacities of the aggregation in winter. The reserve amount is constant for each day and ranges from approximately 1.4 MW on Wednesday to 3.7 MW on Saturday. Therefore, an aggregation of 22 to 60 buildings would be needed to reach the minimum bid size of 5 MW in Switzerland. The high reserve amount during the weekend, which is due to the relaxed comfort zone constraints, introduces a new peak in consumption. The optimal allocation of reserves among the buildings is shown using different colors. Due to the requirement for symmetric control band, the consumption is spread throughout the whole week. Interestingly, the buildings tend to offer more reserves when they normally consume less power. Buildings with system A contribute mainly at night, whereas buildings with system B participate more during working hours, because they prefer to preheat at night.

The consumption of the HVAC system and the room temperature of building A1 are shown in Figures 3 and 4, respectively. The blue curves show the HVAC consumption as scheduled by the MPC controller every 15 minutes, and the resulting room temperature. The red curves show how the power consumption moves around the scheduled value to track the LFC signal, and the resulting temperature trajectory. Note that both the HVAC consumption and the room temperature stay always within the robust region, which is indicated with grey color. Due to the robust design, the HVAC consumption and temperature satisfy the input and output constraints (shown in green in both figures), respectively, for all reserve requests during the week.

5.2 Summer Week

The building aggregation can provide large amounts of reserves also during the summer week, as shown in Figure 5. The minimum amount is approximately 1.5 MW on Monday and the maximum 4 MW on Saturday. In this case, the reserve is more uniformly distributed among buildings with system A and B, since the time constants of cooled ceiling and TABS are similar. Figures 6 and 7 are similar to Figures 3 and 4,

respectively. One difference is that the robust region of room temperature in summer is much narrower compared to that in winter. This can be explained considering how the heating and cooling systems affect building A1. Heating is done using radiators and influences the room temperature directly. On the contrary, cooling is done through the ceiling and affects the room temperature indirectly. This is why the robust region of ceiling temperature is wider, as can be seen in Figure 8.

6. SENSITIVITY ANALYSIS RESULTS

6.1 Capacity Payment

Figure 9 shows the maximum reserve energy as a function of the ratio k/c. We indicate the contributions of buildings with systems A and B with different colors. The maximum reserve energy is calculated assuming that the TSO always requests the reserve capacity from the aggregation. For both winter and summer, the trigger point for reserve provision occurs at the ratio $k/c = 1.1$. For smaller ratios, operating the buildings in a less energy efficient way incurs higher costs than the earnings from the reserve provision. Larger ratios increase the amount of reserves only marginally. In practice, the capacity payment will be determined considering opportunity costs and expectations on the competition.

6.2 Bid Duration and Symmetry

The current reserve market structure with weekly, symmetric bids is very restrictive for participation of building aggregations. Here, we compare four different reserve products: (a) daily duration and symmetric bids ("ds"), (b) daily duration and asymmetric bids ("da"), (c) hourly duration and symmetric bids ("hs"), and (d) hourly duration and asymmetric bids ("ha"). The results for winter and summer are summarized in Tables 1 and 2, respectively. Adopting hourly bids would increase the amount of reserves by approximately 12% in winter and 14% in summer, compared to daily bids. If asymmetric bids are allowed, the buildings prefer to offer more up- than down-reserves in summer, whereas in winter no down-reserves are provided at all. This strategy achieves the best tradeoff between profit maximization and electricity cost reduction.

6.3 Value of Aggregation

To quantify the value of building aggregations, we repeat the analysis of Section 6.2 assuming that each building participates independently in the reserve market. This means that the day-ahead scheduling problem is solved by each building separately, rather than by an aggregator. Our analysis shows that aggregating buildings increases the amount of reserves that can be extracted from them, because they work complementarily to each other. Due to this additional flexibility, comfort constraints and the requirements for reserve duration and symmetry are easier to satisfy, by shifting reserves from one building to another in an optimal way. This is more pronounced in case of daily bids in winter; in this case, the aggregation increases the reserves by approximately 13% for symmetric bids and 15% for asymmetric bids. In summer, the increase is around 3% for both symmetric and asymmetric bids. Therefore, aggregations can help reduce the total number of buildings that are required to offer a certain amount of reserves. However, in case of hourly reserve bids the value of aggregation is much lower, because they are already tailored to the needs of individual buildings.

7. DISCUSSION

Our analysis revealed a large potential for LFC provision by office building aggregations, which can be tapped revising the
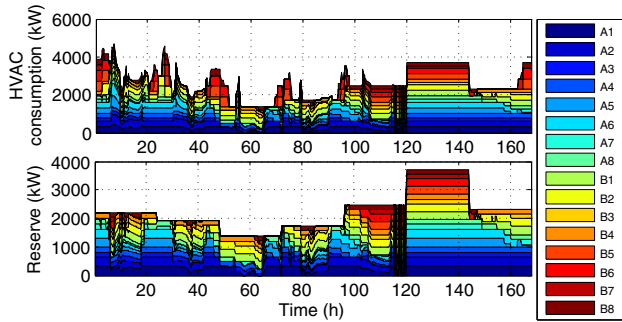
Fig. 2. HVAC consumption and optimal reserve allocation among buildings (winter week).
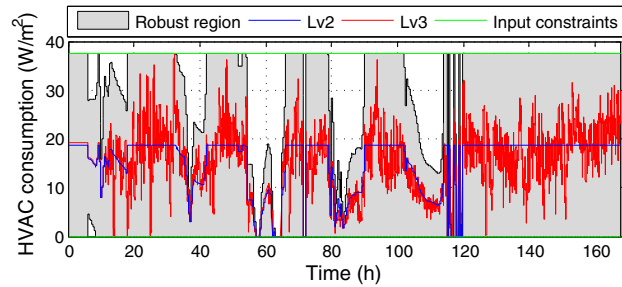

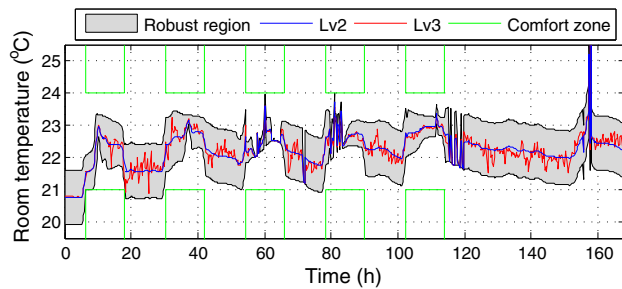Fig. 3. HVAC control inputs for building A1 (winter week).

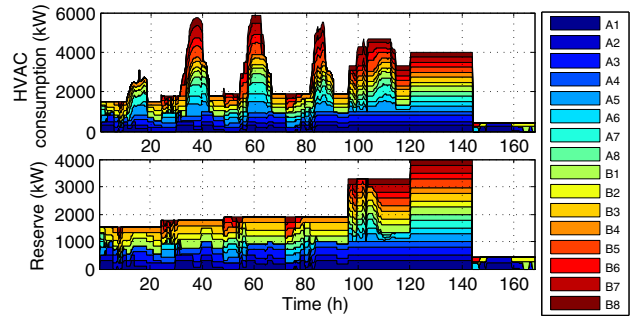Fig. 4. Room temperature for building A1 (winter week).

Fig. 5. HVAC consumption and optimal reserve allocation among buildings (summer week).
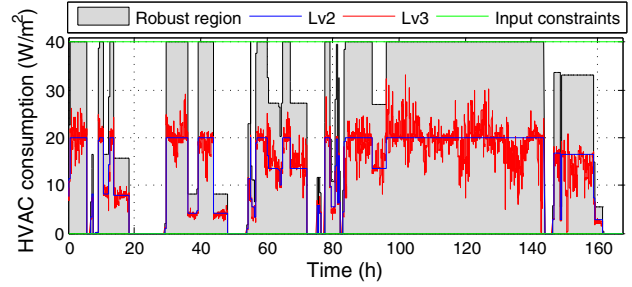

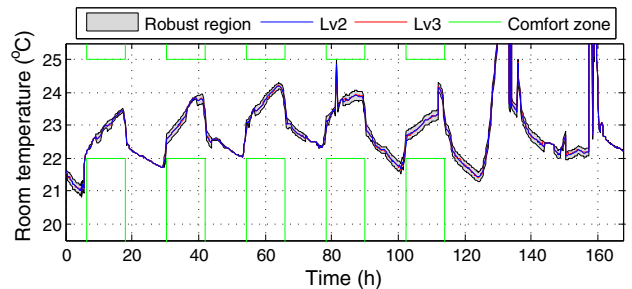Fig. 6. HVAC control inputs for building A1 (summer week).

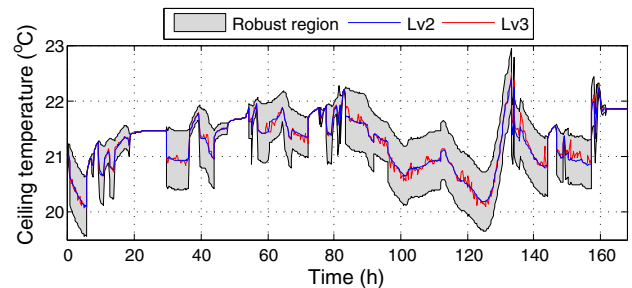Fig. 7. Room temperature for building A1 (summer week).

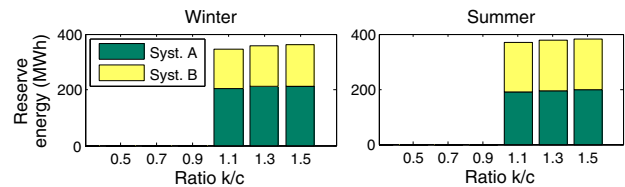Fig. 8. Ceiling temperature for building A1 (summer week).

Fig. 9. Sensitivity of reserve provision on k/c ratio.

current market requirements on bids' duration and symmetry. Due to their large thermal inertia, even small aggregations of around 60 buildings meet the current minimum bid size requirements. Although the reserve scheduling is done in a centralized way, the HVAC control and reserve provision are performed in a decentralized fashion to preserve privacy and reduce real-time communication needs.

To enable reserve provision, the buildings operate in a less energy efficient way. Table 3 shows the total increase in consumption, compared to an energy optimal building control, for the considered bid characteristics, and its breakdown for buildings with system A and B. For each case, the first value is for winter and the second one is for summer. Symmetric bids drastically increase consumption, in particular for buildings with system A in winter. On the other hand, asymmetric bids lead to much more reasonable consumption values for both building types. Due to the increase in consumption, the buildings need strong monetary incentives to provide reserves. Our results indicate that capacity payments at least 10% higher than the retail electricity price are needed. Assuming an average electricity price of 146.6 CHF/MWh, which is the case for consumers with more than 60 MWh/year in Zurich, capacity payments in excess of 160 CHF/MWh are needed. This is approximately 4 times higher than the average capacity payments in 2013, yet significantly lower than the most expensive accepted bids, see Swissgrid [2013b].

Recall that we assumed perfect predictions of weather and occupancy, and no plant-model mismatches. In practice, additional slack must be left to account for such errors. Furthermore, an arbitrary fast reaction of the heating/cooling devices was assumed, neglecting their internal dynamics and constraints. For the above reasons, our analysis provides an upper bound on the amount of reserves that can be robustly offered by build-

ings. Interestingly, buildings can provide reserves even in the theoretically worst case scenario, i.e., $w_t = \pm 1$ for the whole contracted period. However, such a scenario is very unlikely in practice, since the TSO would release the LFC reserves by tertiary control activation and/or redispatch. Less conservative solutions could be obtained by imposing constraints on the maximum reserve energy requested over a period of time, if the TSO can guarantee this. The remuneration of reserve energy was not included in the scheduling problem of this paper. Extending the formulation accordingly could reduce the necessary capacity payments.

Table 1. Effect of bid characteristics on the amount of LFC reserves (MWh) in winter.

Bid	System A	System B	Total reserve
ds	± 202.4	± 144.6	± 347.0
da	$+481.2/-0$	$+309.2/-0$	$+790.4/-0$
hs	± 215.9	± 172.3	± 388.2
ha	$+522.5/-0$	$+367.9/-0$	$+890.4/-0$

Table 2. Effect of bid characteristics on the amount of LFC reserves (MWh) in summer.

Bid	System A	System B	Total reserve
ds	± 190.3	± 181.2	± 371.5
da	$+212.7/-163.9$	$+231.1/-139.3$	$+443.8/-303.2$
hs	± 226.8	± 197.6	± 424.4
ha	$+311.4/-143.5$	$+279.4/-127.0$	$+590.8/-270.5$

Table 3. Energy consumption increase in winter/summer compared to energy optimal operation.

Bid	System A (%)	System B (%)	Total (%)
ds	231.4/113.5	34.1/124.5	97.1/118.8
da	31.6/51.2	0/40.4	10.1/45.0
hs	251.5/129.4	41.3/128.8	108.5/129.1
ha	29.3/32.6	0/32.9	9.4/32.8

8. CONCLUSION

In this paper, we presented a hierarchical control scheme to enable the participation of office building aggregations in power system frequency control. An aggregator determines day-ahead the optimal reserve amount and allocation among the buildings. In real-time, the buildings' HVAC systems are controlled and the reserve is provided in a decentralized fashion, using an MPC and a proportional controller. The proposed scheme is robust since the reserves can be successfully provided even in the worst case of frequency deviation, and without compromising occupants' comfort. Simulation results revealed a large potential for reserve provision from office building aggregations. However, new reserve market designs are needed to leverage the full potential and incentivize building participation.

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