Demand Side Frequency Regulation from Commercial Building HVAC Systems: An Experimental Study

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***Abstract*— Demand side resources can be valuable for providing inexpensive ancillary services to the power grid. This paper present an experimental demonstration of providing frequency regulation from a commercial building Heating Ventilation and Air Conditioning (HVAC) system. The experiments were conducted in Pugh Hall, a 40,000 sq. ft. commercial building located at the University of Florida. In this paper, we describe the steps required to make this possible, including control architecture, system identification, and control design. The field experiments demonstrate: 1. satisfactory frequency regulation service can be provided by the HVAC system without noticeable effect on the indoor climate, and 2. the ancillary services provided by this system passes the qualification criteria for participating in PJM Interconnection's frequency regulation market.**

I. INTRODUCTION

In a power grid, ancillary services are needed to correct the mismatch between demand and supply. With increasing renewable energy integration, the requirement for ancillary services also increases [1]. This paper focuses on frequency regulation, which corrects the short-term imbalance in the grid, usually on time scales of seconds to minutes [2]. There is also a well developed market to incentivize this type of service. The Federal Energy Regulatory Commission (FERC) has recognized the need for increasing ancillary services through several new rulings, such as the recent FERC order 755 [3].

Traditionally, frequency regulation has been provided by responsive power generators. To provide these services, generators must withhold power, which leads to additional cost in terms of both fuel and maintenance. Ramping of generation output also has cost in the form of additional pollution [4]. Finally, it is costly to build new generators to satisfy the increasing demand for ancillary services.

Recent research have shown that the demand side is capable of providing abundant high quality ancillary services at various time scales [5–8]. Buildings are a tremendous untapped resource for several reasons. First, they are large energy consumers, accounting for 74% of total electricity consumption in the U.S. [9]. Residential loads, such as air conditioners and pool pumps, can be aggregated to provide ancillary services; see for example [8, 10–12]. Manufacturing companies such as Alcoa Inc provide demand side ancillary services today in a range of time scales [13].

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HVAC systems in commercial buildings in particular have significant potential as providers of inexpensive and high-quality ancillary services [6, 7, 14]. The large thermal inertia of commercial buildings makes it possible to vary power consumption of the HVAC system without compromising its primary functionality. Most commercial building HVAC systems have continuous control variables, which provides flexibility in control design compared to on-off control commonly used in residential air conditioners. Also, commercial buildings are usually equipped with Building Automation System (BAS), which simplifies the installation of new control algorithms.

Previous work has shown, from theory and simulations, the potential of providing frequency regulation from supply air fan in the Air Handling Unit (AHU) in a commercial building [6, 7, 15]. In this paper we report implementation of a control scheme in a real building to provide frequency regulation and discuss results of the experiments. The field experiments are carried out in Pugh Hall, a 40,000 ft^2 building on the University of Florida campus that has a Variable Air Volume (VAV) HVAC system.

The experiments reported here demonstrate that a building HVAC system can provide frequency regulation service inexpensively without affecting its primary responsibility — maintaining comfortable indoor climate. This work is inspired by our prior, simulation-based, studies on using HVAC fans to provide frequency regulation [6, 15, 16]. However, the control architecture used here is quite distinct from those in our prior work. A feedback control architecture is introduced to extract ancillary services by varying fan power consumption. In particular, the supply air flow rate set-point is controlled to change the fan power indirectly. The controller design is based on a black-box transfer function obtained through system identification experiments.

The control algorithm is tested with filtered regulation signals obtained from PJM: the Area Control Error (ACE) signal as well as the dynamic regulation signal (RegD). Results show that the control system introduced here provides satisfactory performance in the frequency range of $f \in [1/(10 \text{ min}) \ , \ 1/(1 \text{ min})]$, and pass the PJM qualifying test [17].

Based on these experimental results, we estimate the economic value of building used in these experiments if it were to take part in PJM's ancillary services market, and the total amount of ancillary services that similar commercial buildings in the U.S. can provide through software retrofit.

The rest of the paper is organized as follows: in Section II, we briefly describe typical HVAC systems in commercial buildings and the proposed control architecture. In Section III, we introduce the testbed where the experiments were carried out. In Section IV, models of HVAC system are identified experimentally for controller design and analysis. The controller design is discussed in Section V. Experimental results are provided in Section VI. Section VII concludes the paper and discusses future work.

II. Problem formulation

The control architecture described in this section is a software add-on for an existing HVAC control system. We first briefly review typical HVAC systems before describing this control architecture.

A. Typical HVAC system in a commercial building

Fig. 1 shows the schematic of a VAV HVAC system; 30% of U.S. commercial building floorspace is serviced by such systems [18]. A part of return air is mixed with outdoor air, which is cooled and dehumidified while it passes through the cooling coil in the AHU. The air is distributed to terminal devices, called VAV boxes, through ducts for distribution into individual zones. A supply air fan motor in the AHU provides the mechanical energy required to circulate the air.

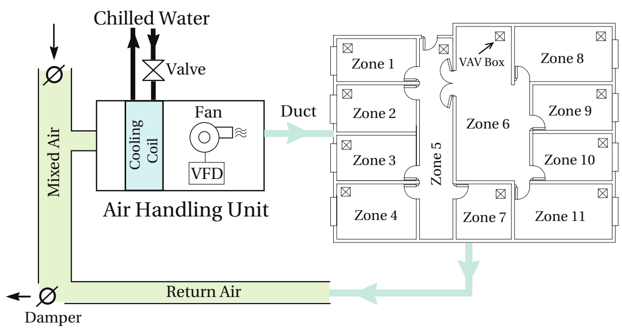

Fig. 1. Typical commercial building VAV HVAC system.

The fan control loop and zone climate control loop are two of many control loops in a HVAC system that are important to the discussion in this paper. These two loops are shown in Fig. 3. The zone climate controller compares the measured zone temperature T to a predetermined setpoint T_{ref} to compute a desired supply air flow rate m_{ref} to achieve the desired zone climate. The fan controller computes the fan command u_f to ensure that the supply air flow rate m_a tracks m_{ref}. In a VAV system, the fan motor speed is varied through a Variable Frequency Drive (VFD), so the command u_f is sent to the VFD. The fan command u_f is measured in the unit of % of the maximum speed.

B. Proposed control architecture

In this paper we assume that a building HVAC system that provides frequency regulation service receives a signal from a Balancing Authority (BA), denoted by δP_{BA}, which is then filtered with a bandpass filter to generate a local reference signal, δP_r (in unit of Watts). Fig. 2 illustrates the proposed control architecture. The HVAC system's responsibility is to vary its power consumption so that the deviation from its baseline power tracks the reference signal δP_r. The baseline power is the power the HVAC system would have consumed if it were only maintaining indoor climate and not providing ancillary services.

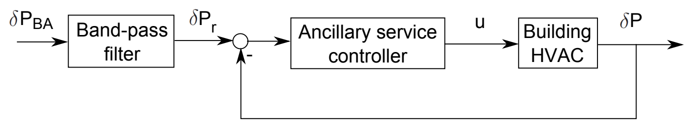

Fig. 2. Proposed control architecture.

The design problem considered in this paper involves the *Ancillary Service Controller* (ASC), which is local to the building. This controller addresses a reference tracking problem: commands to the AHU fan are modified in real-time so that δP, the measured deviation from the baseline power, tracks the reference deviation δP_r. Algorithms to estimate the deviation from baseline in real-time are described at the end of this section.

Recall that the primary functionality of the load must not be compromised in extracting ancillary services. Variations in the airflow rate introduced by the ASC may affect the indoor climate. Moreover, the existing climate control system may "correct" the variations in the airflow introduced by the ASC's command, since the latter appears as a disturbance to the climate control loop.

Ancillary services can be provided without running into these issues if the reference signal δP_r is chosen to be of higher frequency than the bandwidth of the climate control system, so that the climate control system does not reject the disturbance due to the ASC. The thermal inertia of the building will low-pass filter the effect of the ASC so that the indoor climate will not be affected. In addition, the reference signal δP_r should be small enough in magnitude so that the resulting variations in airflow rate do not lead to noticeable changes to the indoor climate. The passband frequencies and gains of the bandpass filter that filters δP_{BA} to produce the local reference signal δP_r have to be designed to satisfy these two constraints. Due to the constraint of having little effect on the indoor climate, the proposed architecture is suitable for high-frequency ancillary services such as frequency regulation, but may not be suitable for low-frequency ancillary services such as load following.

The control signal u in Fig. 2 could be any command that changes the power consumption of the HVAC system. In this paper, we choose to control the supply air flow rate set-point m_{ref}; see Fig. 3. A change in the flow rate will result in a change in the fan motor power consumption.

The ASC described here is implemented as a software add-on to the existing climate control system; details are provided in Section III. As a result, the ASC does not override the existing HVAC control system, it merely modifies the

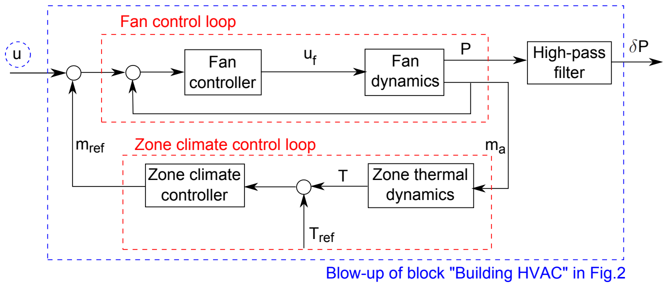

Fig. 3. Location to inject control command u in the local control loop.

commands in the HVAC system.

The deviation δP is not directly measured; instead only the power measurement P is available from the VFD. To obtain δP, we take advantage of the fact that reference signal has higher frequency than the dynamics of building HVAC system. The baseline power can be estimated online by passing P through a low-pass filter. The deviation from baseline, δP, can then be estimated by subtracting the estimated baseline from P. This is equivalent to using a high-pass filter; see Fig. 3. We denote this estimated power deviation by $\delta \hat{P}$.

III. Test bed

The field experiments are carried out in 40,000 ft^2 building on the University of Florida campus, Pugh Hall. It has a VAV HVAC system with 3 AHUs. We choose AHU2, which is dedicated to a single auditorium, for conducting the tests.

Although Pugh Hall is equipped with a BAS (Siemens' APOGEE$^{\text{TM}}$ system), the BAS is not convenient for executing third party control algorithms in the building's equipment. A custom software was used to read values from and write commands to the HVAC equipment (fan power consumption, airflow rate setpoint, fan speed setpoint). The software is designed to simultaneously support a number of applications by interacting with various databases. Control commands from the applications are communicated to the software by appending a row to a table in a relational database. A scheduler, which checks for such updates every second, then communicates these new commands to the HVAC equipment through BACnet [19]. In our experiments, inputs were commanded at 4 second intervals and outputs were averaged and/or interpolated to generate values sampled at 4 second intervals. Partial details of the software are described in [20].

During the experiments, control commands are executed by modifying commands from the building's climate control system without replacing the climate control system. For instance, to control the supply air flow rate set-point, the value computed by the local building climate control system is read first; the value of u is computed by the ASC and is added to the local command. The sum was sent to the building BAS through the software.

IV. System identification

Design and analysis of the ASC requires a model of how the command u affects the fan power. However, dynamics of HVAC systems are highly uncertain, so modeling from first principles is likely to be inaccurate. In this section we describe how an input-output model was fit to data obtained at our test bed.

It is known that a physics-based model for HVAC system dynamics is nonlinear. For the purposes of control, it is found that a linear input-output model can be fit to data within the frequency range of interest. The input of the system is the deviation to the supply air flow rate, i.e., u; while the output is the power deviation from its baseline power profile, i.e., δP. We denote the input-output models from u to δP as H.

Frequency domain identification is preferable to fitting a parameterized linear model because of strict constraints on the magnitude of the inputs. Due to the large measurement noise, the sine-sweep method was used for estimating the frequency response [21].

Sine-sweep tests were conducted by modifying the supply air flow rate command through the control software in such a way that u becomes a sinusoidal signal with given frequency. In these experiments the nominal fan power was equal to 2.5kW, and for each frequency, the number of data points collected was approximately 500.

Frequency response data of H were obtained from the sine-sweep experiments. A second-order transfer function is fitted to the experimental data:

$$\hat{H}(s) = \frac{1.809 \times 10^{-5}}{s^2 + 0.04455s + 0.01205}, \tag{1}$$

The results of these experiments are summarized in the plots shown in Fig. 4. The frequency response shows that the system has a nearly constant gain in the range $f \in [1/(10 \text{ min}) \ , \ 1/(1 \text{ min})]$, which simplifies control design to track reference in this frequency range.

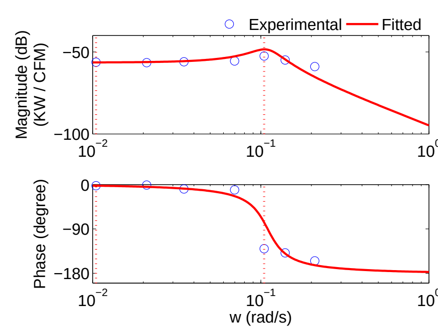

Fig. 4. Frequency response of H identified from sine-sweep experiments, as well as the Bode plots of the fitted transfer functions.

V. Compensator design

Recall the discussion in Section II-B: large variation in the fan speed or air flow rate is to be avoided. Such variations are undesirable also due to the possibility of equipment damage and violation of indoor air quality standards [22]. In addition, the fan speed command is subject to magnitude constraints, since it takes values between 0 and 100%.

For these reasons, the frequency ranges for providing ancillary services are chosen where the system has large gain. Considering the frequency response identified in Section IV, the frequency range of interest are chosen to be $f \in [1/(10 \text{ min}) \ , \ 1/(1 \text{ min})]$. The controllers are designed to ensure closed loop stability and close-to-unity gain of the closed loop frequency response in their respective frequency bands of operation.

We do not attempt to track reference signals of frequency lower than $1/(10 \text{ min})$. If air flow rate is varied at such slow time-scales, power consumption at the chiller will be affected, which we wish to avoid. Variations in air flow rate at higher frequency ranges, on the other hand, will be "filtered out" by the low-pass characteristics of the chiller, and hence do not impact power consumption at the chiller [7].

A lag compensator was chosen:

$$C_{lag}(s) = k\frac{s-z}{s-p} \tag{2}$$

where the pole was set to $p = -0.0017$, the zero was set to $z = -0.6283$, and gain was set to $k = 30$. The frequency response of the closed-loop system is shown in Fig. 5. Good tracking performance is expected since the gain of the closed loop transfer function $H^{ry}(j\omega)$ is nearly unity in the frequency range of interest, $f \in [1/(10 \text{ min}) \ , \ 1/(1 \text{ min})]$.

Assume that the supply air flow rate is allowed to vary within 1000 cfm of its nominal value and the reference signal to be tracked has a peak magnitude of 1kW. This is equivalent to have a limit of $|H^{ru}(j\omega)| \leq 60dB$, which is also met in the frequency range of interest; see Figure 5. Thus, with this lag compensator, good tracking performance is obtained with small actuation.

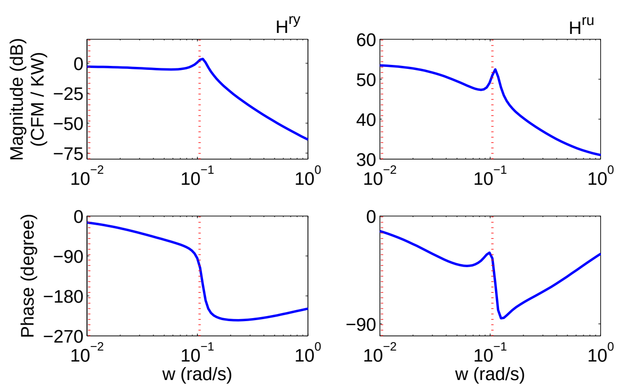

Fig. 5. Closed-loop frequency response with the designed ASC. Left: from reference signal to output - $H^{ry}(j\omega)$; right: from reference signal to control command - $H^{ru}(j\omega)$. The vertical lines indicate the frequency range of interest.

VI. Experimental results

A. Reference signals and bandpass filters

Two distinct reference signals (δP_r) are used in the simulations and experiments in this paper. The first one is obtained using the ACE signal as δP_{BA}; in particular, ACE data from PJM on 05/04/2009. A tenth-order Butterworth filter was used to obtain δP_r. The passbands of the corresponding bandpass filters are chosen to be $f \in [1/(10 \text{ min}) \ , \ 1/(1 \text{ min})]$. The filter gain is chosen so that the peak amplitude of δP_r is approximately 1kW. In the sequel, we will call the first δP_r the *filtered ACE*. The second reference signal is the RegD signal, which is broadcast by PJM to frequency regulation participants. In this case the bandpass filter is simply a gain of 1kW.

B. Performance Criteria

The dual goals of the ASC are frequency regulation to the grid, while maintaining indoor climate quality as well as low cost to the building operator. Metrics to quantify performance are described here.

ancillary services: A natural metric to quantify the quality of tracking error $e(i) := \delta P_r(i) - \delta \hat{P}(i)$ is the ratio,

$$r_R = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N} e(i)^2}}{\max |\delta P_r|} \tag{3}$$

in which the numerator is the root mean square of the error and the denominator is the maximum of the reference signal.

We also evaluate the ASC using PJM's performance score S_t, based on the formula given in their manual[17]. The total performance score S_t is the mean of three scores: correlation score S_c, delay score S_d, and precision score S_p. A score of $S_t \geq 0.75$ is required to qualify to take part in PJM's ancillary services market.

Indoor climate: Indoor climate quality is quantified using the temperature violation D_T defined in [23]. This score is 0 if the temperature is between $70°F$ and $75°F$ and score increases if the temperature deviates from these bounds. These bounds are chosen according to the thermal comfort specifications described in Chapter 8 of [24].

Variation in supply air flow rate comes with some cost. This variations are quantified by,

$$\delta \bar{m} = \frac{\sum_{i=1}^{N} \left| \frac{m(i) - m_b(i)}{m_b(i)} \right|}{N}, \tag{4}$$

$$\delta m_x = \max_i \left| \frac{m(i) - m_b(i)}{m_b(i)} \right| \tag{5}$$

where m is the measured supply air flow rate, and m_b is the baseline supply air flow rate.

C. Experiments setup and results

Each experiment was conducted over a 40 minutes time duration using AHU2 of Pugh Hall. Forty minutes is equal to the length of the test required by PJM to meet their qualification criteria [17]. Commands from the ASC were executed by modifying the commands from the building's existing climate control system, as described in Section III.

We observed from historical Pugh Hall data that under the existing building climate control system, the frequency of fan power variation is lower than $1/(30 \text{ min})$. Thus in all closed-loop control experiments, the high-pass filter to obtain the power deviation from the baseline was chosen as a 1^{st}-order Butterworth with cutoff frequency at $1/(30 \text{ min})$. The component in the power measurements with lower frequencies than the cutoff frequency is the baseline from the existing building climate control system.

Data from two typical runs are shown in Fig. 6. The total fan power data are also provided in Fig. 7. The control system's scores summarized in Table I exceeded PJM's threshold for both reference signals. The indoor climate results are shown in Table II. Fig. 8 and 9 show the room temperature and supply air flow rate profiles during the day of the filtered ACE experiment. The results for the RegD experiment are similar, and is omitted due to limited space. From these table and figures, we see that the effect on room climate is negligible, and the airflow rate variation is small.

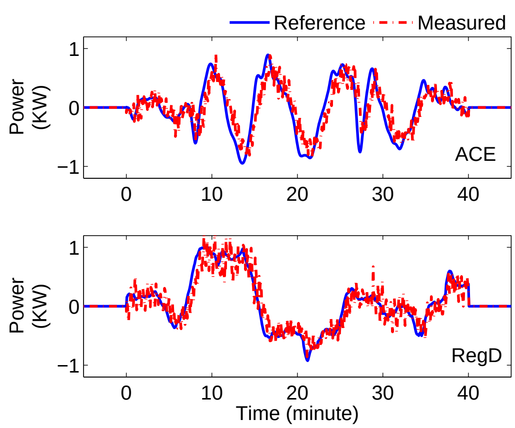

Fig. 6. Experimental result of ASC. Top: filtered ACE as reference signal; bottom: RegD as reference signal.

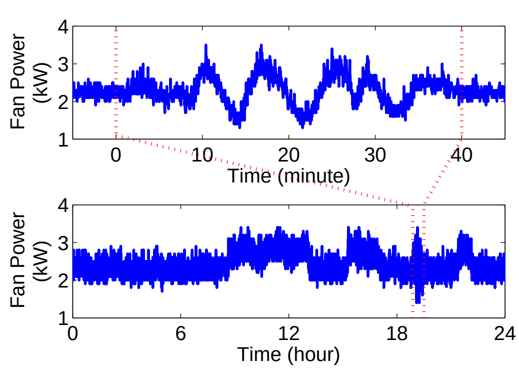

Fig. 7. Total fan power data for the filtered ACE experiment. Top: 40-minute profile during the experiment; bottom: 24-hour profile during the day of the experiment.

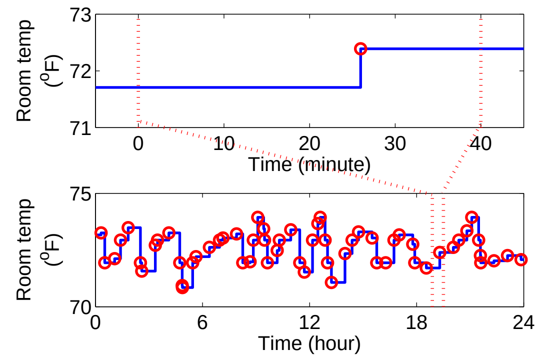

Fig. 8. Effect of ACS on room temperature for the filtered ACE experiment. Top: 40-minute profile during the experiment; bottom: 24-hour profile during the day of the experiment.

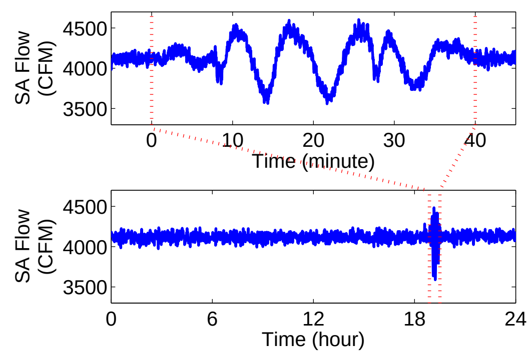

Fig. 9. Effect of ACS on supply air flow rate for the filtered ACE experiment. Top: 40-minute profile during the experiment; bottom: 24-hour profile during the day of the experiment.

D. *Economic potential*

What is the economic value of Pugh Hall or similar buildings to a BA? The payment schemes used by ISOs are currently in a state of flux due to the recent FERC order 755 [3]. In this paper, we provide an estimate of the revenue that can be obtained from PJM can be computed based on their publicly available policy manuals [25, 26].

In the Pugh Hall experiments, AHU2 was operating at 2.5kW. Results show that AHU2 can easily provide 1kW capacity of frequency regulation during its operational hours: 6 am to 11 pm. There are two other AHUs which normally operates at 7kW and 5kW. Assuming that all 3 AHUs provide

TABLE I

PERFORMANCE RESULTS FOR EXPERIMENTS.

Reference	r_R	PJM performance score			
		S_c	S_d	S_p	S_t
Filtered ACE	0.27	0.94	0.94	0.44	0.77
RegD	0.19	0.94	0.95	0.60	0.83

TABLE II

EFFECTS OF ASC ON ROOM CLIMATE.

Reference	D_T	$\delta\bar{m}$ (%)	δm_x (%)
Filtered ACE	0	3.4	13.8
RegD	0	3.9	15.0

the same ratio of their nominal power for ancillary services as AHU2 does, Pugh Hall's HVAC system can provide 5.8kW of capacity. Time-varying market data was obtained in 2013 from the PJM website [27]. Assuming that the building provides 5.8kW of capacity of RegD service during each of its operational hours, the yearly revenue for Pugh Hall is estimated to be $\$1,421$. The total maximum capacity of the AHUs is 75kW, and more revenue can be generated if the AHUs operate at higher power.

VII. Discussions and Future Work

Fan motors in commercial building HVAC systems can provide frequency regulation service to the power grid without impacting indoor climate. This has been demonstrated through field experiments in this paper using a feedback control architecture, designed to provide ancillary services in specific frequency ranges. In fact, the system was able to provide ancillary services in frequencies that are higher than that of the fastest reference signal provided by PJM, RegD.

Experimental results at Pugh Hall at the University of Florida show that these algorithms pass the qualifying tests to participate in PJM's frequency regulation service market. This 40,000 sq. ft. building would generate approximately $1,400 revenue per year based on PJM's 2013 prices.

There are many directions for future research. First, there are many other loads in a building with slower dynamics, such as chillers, that can be used to provide ancillary services in longer time scales. Baseline power estimation becomes an issue at longer time scales since the time-scale separation utilized in this paper no longer hold. A control architecture for using chillers to provide ancillary services in the frequency band $f \in [1/(1 \text{ hour})\ ,\ 1/(3 \text{ min})]$ was presented in [7], but it did not address the baseline estimation problem. A more comprehensive solution to the problem is presented in a companion paper [14]. Much work remains to be done on the question of how to use demand side resources to provide ancillary services in the longer time scales. Second, the control architecture proposed in this paper is a software add-on. Improvements in hardware and software can lead to better performance (e.g., improving measurement accuracy and reducing execution delay). Third, further thoughts on information architecture should be considered in future work.

Acknowledgments

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