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International High Performance Buildings Conference

School of Mechanical Engineering

July 2018

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Building HVAC Flexibility Estimation and Control for Grid Ancillary Services

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ABSTRACT

This paper presents data-driven methods for estimating the demand flexibility of commercial buildings' Heating Ventilation and Air Conditioning (HVAC) system and the control architecture to enable the execution of committed grid reserves while ensuring quality of service. In particular, we describe the methodology for 1) qualifying the HVAC system to provide three power grid ancillary services (frequency response, frequency regulation and ramping services) based on defined metrics for response and ramp time, 2) quantifying the magnitude and frequency bandwidth of the service it can provide, and 3) controlling the building thermal demand within the specified flexibility limits to provide frequency regulation service. UTRC's high performance building test-bed, a medium-sized commercial office building is used for the experimental study. The building testing is focused on the air-side electricity consumer - the supply air fans in the air handling unit (AHU). The resulting data verifies that air-side HVAC loads (ventilation fans) are sufficiently responsive to meet the requirements of frequency regulation (<5 seconds response time) and ramping services (<10 minutes response time) with ON/OFF control command, direct fan speed control, and indirect control through building duct static pressure set-point adjustment. The proposed frequency regulation control changes the command to the AHU fan motor speed (and hence power consumption) by indirectly modifying the duct static pressure set-point to track a given regulation reference signal. This architecture is selected for equipment reliability and the ease of implementation. The experimental frequency response data from static pressure set-point to AHU fan power consumption shows that each ventilation fan can provide up to 1.7 kW (18.9% of its rated power) for frequency regulation during operational hours without impacting the indoor climate or baseline controls, and the acceptable frequency range is identified as 0.0055 - 0.022 Hz based on the grid response metrics and controls requirement. The performance of the frequency regulation controller is verified through a closed-loop active response experiment.

1. INTRODUCTION

The increased adoption of intermittent renewable energy, such as wind and solar, onto the electrical grid is increasing the need for greater demand flexibility and the development of more advanced demand management solutions. For example, in March 2017 solar and wind power generation set record highs in California, contributing over 49% of its power supply. Furthermore, Hawaii has committed to meeting 100% of its electrical demand from renewables by 2045. This transformation requires solutions to robustly and cost-effectively manage dynamic changes on the grid while ensuring quality of service. Advanced demand response approaches are a key way of enabling this required grid flexibility. Advances in direct digital control of building systems, combined with the increased connectivity of end devices now enable greater participation. To achieve this, end devices will need to estimate the amount of grid services (flexibility) they can offer, and then automatically fulfil that commitment when called upon without noticeable loss in quality of service (e.g. indoor comfort).

Electric ancillary services are critical to ensure continuous balance of power grid supply and demand. In particular, frequency regulation (FR) is deployed to offset fast and short term fluctuations in load and maintain the system at a prescribed frequency, which is 60Hz in North America. Traditionally, FR services are provided by conventional generators, which reserve some capacity for ramping up or down according to the power grid's needs. Effective integration of fast response demand-side resources will not only improve the grid efficiency but will lower the required operating reserves (Makarov *et al*., 2008). The grid resources can offer FR services by bidding their capability into ancillary service markets for specific hours of the day. The FR capability is the amount of change in power usage an asset can offer to the grid. While the precise market mechanisms and incentive design differ by region and is evolving, the FR compensation depends on a resource's accuracy of performance. For example, in the PJM Interconnection, the engaged resources are compensated based on a composite performance score (an average of correlation, delay and precision scores) which reflect the resource ability to track the regulation signal (PJM, 2017).

HVAC systems in commercial buildings (CBs) have been recognized as valuable resources for maintaining stable grid operation due to their (1) large electric load as CBs accounts for about 40% of the total US electricity, and half of it is consumed by HVAC (US DOE, 2011), 2) large thermal mass that enables the building to be responsive with no impact on the indoor quality and 3) capability for continuous modulation enabled by the variable frequency drives that operate HVAC equipment (such as fans, chillers, pumps), and the Building Automation System (BAS) that can monitor the system power consumption and controls the variables needed to track a given FR signal. Most of the early works on leveraging a building's thermal mass focus on low frequency changes in demand such as load shifting and peak shaving (Braun, 1990, Morris *et al*., 1994, and Ma *et al*., 2010). Recently the use of buildings as resources for high quality fast ancillary services has received a lot of attention (see Lin *et al*., 2013, Hao *et al*., 2014 for example). Accurate determination of the building flexibility is equally important to ensure the building's quality of service is not compromised while providing the grid services. A virtual battery model was developed to represent a collection of thermostatically loads (Hao *et al*., 2013) and has been extended to characterize the flexibility of CBs HVAC systems (Hughes et al. 2016, Hao *et al*., 2017, Lin and Adetola, 2018).

In this paper, we summarize the work performed at UTRC to 1) qualify a HVAC ventilation fan to provide fast ancillary services based on defined metrics for response and ramp time, 2) quantify the magnitude and frequency bandwidth of the FR service it can accurately provide without impacting the building occupants' comfort and 3) control the building's air-side power usage in response to the grid needs. The flexibility characterization and controls experiments were performed on a medium sized office building with 2 Air Handling Units (AHUs) and 40 Variable Air Volumes (VAVs). The performance of the frequency regulation controller was quantified using DOE NODES program performance metrics (ARPAE, 2015) and PJM performance scores (PJM, 2017). While there is growing literature on the use of HVAC fans to provide frequency regulation services, the experimental demonstration of the capability has been very limited. The control architecture proposed by Lin *et al*. (2015) utilizes either the fan speed command or airflow rate set-point to adjust the fan motor power consumption, whereas this work demonstrates the use of building duct static pressure set-point to realize the FR objective. Moreover, we provided a functional testing procedure and analysis for characterizing, a-priori, the flexibility of the HVAC equipment in terms of FR capacity and frequency band for which it can successfully track a FR signal. The experimental approach is necessary to capture short-term mechanical and momentum dynamics of the HVAC system that may impact its performance for frequency regulation, and for which accurate representation in a modeling environment is difficult.

The experiments verify that air-side HVAC loads (ventilation fans) are sufficiently responsive to meet the requirements of frequency regulation. The flexibility quantification analysis shows that each ventilation fan can provide up to 1.7 kW for frequency regulation (18.9% of its rated power) during operational hours without impacting the indoor climate, and the acceptable frequency range is identified as 0.0055 - 0.022 Hz based on the grid response metrics and controls requirement. The closed-loop results validated the performance of the proposed frequency regulation controller.

2. HVAC SYSTEM CHARACTERIZATION

In this section, we describe the methodology for 1) qualifying the HVAC system to provide ancillary services to the power grid and 2) quantifying the magnitude and frequency bandwidth of the FR service it can provide. UTRC's high performance building test-bed (HPBT), a medium-sized commercial office building with two Air Handling Units (AHUs) and 40 Variable Air Volume (VAV) terminal units was used for the experimental testing. Each of the AHU's is connected to multiple VAV boxes (with reheat coils). The building is operated with a building management system from Automated Logic Corporation (ALC) and can be monitored through its WebCTRL interface. The real building functional testing is focused on the air-side electricity consumer - the air fans in the AHU. The building has a total of 4 fans (2 supply and 2 return fans). The experimental results presented are for the supply fan that serves 15 interior zones, mostly conference rooms and multi-occupant offices. The main assumption is that the chilled water loop is decoupled from the ventilation fans power consumption due to the small and fast fan power variation during frequency regulation control. The supply air temperature set-points to the zones are kept constant during the experiments.

2.1 Requirements

The qualification requirements of three types of ancillary services: primary frequency response, frequency regulation, and ramping services are given in Table 1. The key requirements are concerned with the response time, the ramp time, the reserve magnitude and how long it can provide the service; see Figure 1.

Table 1: Grid service qualification requirements (ARPA-E, 2015)

Service Type	Response Time	Ramp Time	Duration	Reserve magnitude target (RMT % load)
Primary Frequency Response	< 2 seconds	< 8 seconds	>30 seconds	>2%
Frequency Regulation	< 5 seconds	<5 minutes	>30 minutes	>5%
Ramping service	< 10 minutes	<30 minutes	>3 hours	>10%

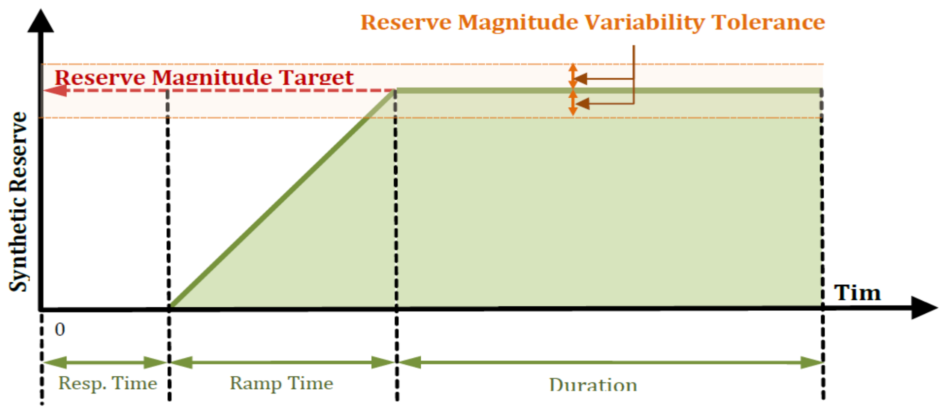

Figure 1: Interpretation of grid services qualification metrics

2.2 Qualification Test

The qualification test includes procedures that vary the real building fan power consumption by 1) commanding the fan on and off, 2) changing the fan speed directly and 3) changing the duct static pressure (DSP) set-point input to the fan speed controller. The functional testing for AHU fan response to ON/OFF commands turn the fan ON or OFF and accurately capture the time the fan is commanded, when the fan power turns non-zero or starts to decrease and the time the power profile reaches steady state. The fan speed-to-power functional test reduces or increases the fan speed from a steady-state condition by increments of 25% and accurately captures the instant the fan speed changes were commanded, the instant the fan power value changed, the fan speed feedback and the power profiles. Similarly, the static pressure set-point-to-power experiment reduces or increases the DSP from a steady-state condition by increments of 0.25 in H_20 and accurately captures the set-point commands, the static pressure feedback and the fan power response. Figure 2 shows a sample incremental step changes in the static pressure set-points, fan speed and fan power consumption.

The experimental results are summarized in Table 2. The AHU fan qualifies to provide frequency regulation and ramping services based on the response and ramp time metrics in Table 1. The three control modes (ON/OFF, direct AHU speed modification, and closed-loop control of DSP) all resulted in satisfactory dynamics. The On-to-Off control mode has the fastest response and ramp time (1 and 5 secs respectively), while the DSP control has the slowest response time of 4-6 secs and ramp time of 38-64 seconds. In the next section, we will show that the ventilation fan also meet the reserve capacity and operational duration metrics.

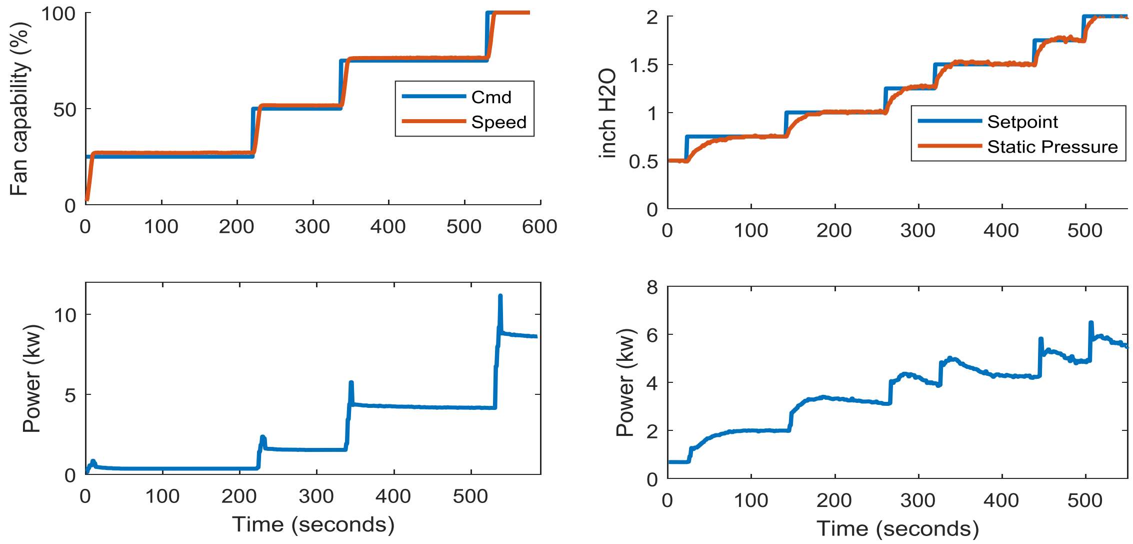

Figure 2: Fan power response to AHU fan speed (left) and DSP set-point (right).

Table 2: Summary of AHU fan qualification results

FR metric	**Requirement**	**Control mode**			
		Off – On	**On – Off**	**Fan speed**	**DSP Control**
Response time (sec)	5	2	1	2	4 -6
Ramp time (sec)	300	32	5	8-12	38-64

2.3 Quantification Test

The building load flexibility is defined as the acceptable perturbations to the baseline power that can be achieved with no undesirable reduction in comfort and ventilation. Baseline or nominal power is defined as the power the building would have consumed were it not providing the grid services. A virtual battery model can be used to describe the flexibility of grid resources. This simple representation, depicted in Figure 3, enables easy aggregation of diverse energy resources and efficient allocation of power reserves to the engaged DERs. It also facilitates comparison with electrical storage as the model is described by familiar parameters such as discharge rate and power limits. Different approaches such as model-based functional testing (Hughes *et al*., 2016) and optimization-based techniques (Hao *et al*., 2017) have been proposed to determine the equivalent parameters and power and capacity limits of the battery model for commercial building HVAC systems.

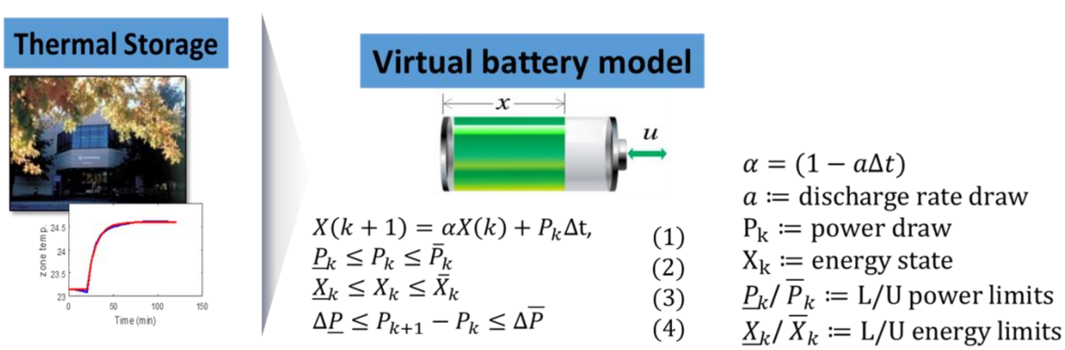

Figure 3: Virtual battery model representation of a building

In this paper, we focus on quantifying the building HVAC ventilation fan for frequency regulation service. The service corrects short-term imbalance on the power grid and the FR reference signal is usually high in frequency and energy neutral on average. Noting that such high frequency change in the fan power consumption will have minimal impact on the indoor environment due to commercial buildings' large thermal mass and inertia, it is sufficient to characterize the building HVAC flexibility for FR in terms of power magnitude (Figure 3, eqn. 2) and rate limits (Figure 3, eqn. 4). To this end, we describe the procedure we used to determine the reserve magnitude and limits on the frequency range for which the building ventilation fan is most effective.

The frequency bands are limited by the equipment operational constraints and the indoor climate requirements. Low frequency variation in the fan speed and hence fan power could result in significant temperature variations, and the existing zone climate controls would react and reject the temperature deviation, resulting in degraded quality of the ancillary service. Similarly, the fan capability to track a "very" high frequency signal could be limited by the equipment operational constraints such as the fan motor ramp-up and ramp-down rate limits that are enforced by the baseline controls to prevent the equipment damage.

The UTRC HPBT fan controller uses the building duct static pressure (DSP) sensor to modulate the supply fan motor speed, and maintain the static pressure at a desired set-point. As the space temperature deviates from set-point, the zone controller responds by adjusting the damper position to increase or decrease airflow. Varying the zone damper position causes the pressure inside the supply ductwork to change, causing the controller to adjust the fan speed (and hence supply airflow). The static pressure set-point could be a constant or varied using Trim & Response logic, which resets the set-point based on zone damper position. The operation of the return air is synchronized with the supply fan and runs at 90% of the supply fan speed. For frequency regulation, the fan power consumption can be continuously modulated by varying the fan speed directly or changing the static pressure set-point to the fan controller. The latter is selected for consistency with the baseline controller and to minimize potential reliability issues. Unlike the direct fan speed control, this architecture ensures that the local fan motor constraints will always be satisfied.

The objective of the qualification test is to determine the reserve magnitude and frequency range at which fan power can provide frequency regulation without impacting the building zones thermal comfort. A sequential iterative scheme was used for the experiment design. The set-point input is a sinusoidal signal ($DSP_{sp}^{nom} \pm$ A sin wt), where the perturbation A is selected to respect the allowable DSP when the building is operating:

$$A \in [0.25,\ \mathrm{A_{max}}], \qquad A_{max} = min\left(DSP_{sp}^{max} - DSP_{sp}^{nom}\ ,\ DSP_{sp}^{nom} - DSP_{sp}^{min}\right) \tag{5}$$

and the frequency w lies within the band:

$$w \in [1/(10\,min), 1/(30\,sec)] \tag{6}$$

For this experiment, the nominal DSP set-point was 1.75 in H_2O and nominal fan power consumption was 3.93kW.

The generated frequency response data from DSP set-point to AHU fan power consumption and zones temperature variation are shown in Figure 4. The indoor climate quality was maintained during the experiment, with the temperature within $\pm 1^{o}$F of the set-point. The comfort range, determined by the baseline controls, differs from zone to zone but they are all at least $\pm 1^{o}$F. The frequency response plot of the experimental data is provided in Figure 5. The fan power can provide up to 1.7 kW (18.9% of its rated power and 43% of its nominal power) of frequency regulation reserve during operational hours without impacting the indoor climate or baseline controls. Since the reserve capacity varies with the frequency of the DSP set-point input, the frequency limits are selected considering controls requirement in addition to the discussed metrics. In particular, the frequency range where the system has large gain is preferred to minimize the control action (fan motor speed command) needed to achieve the regulation goal. The summary of the fan flexibility is provided in Table 3.

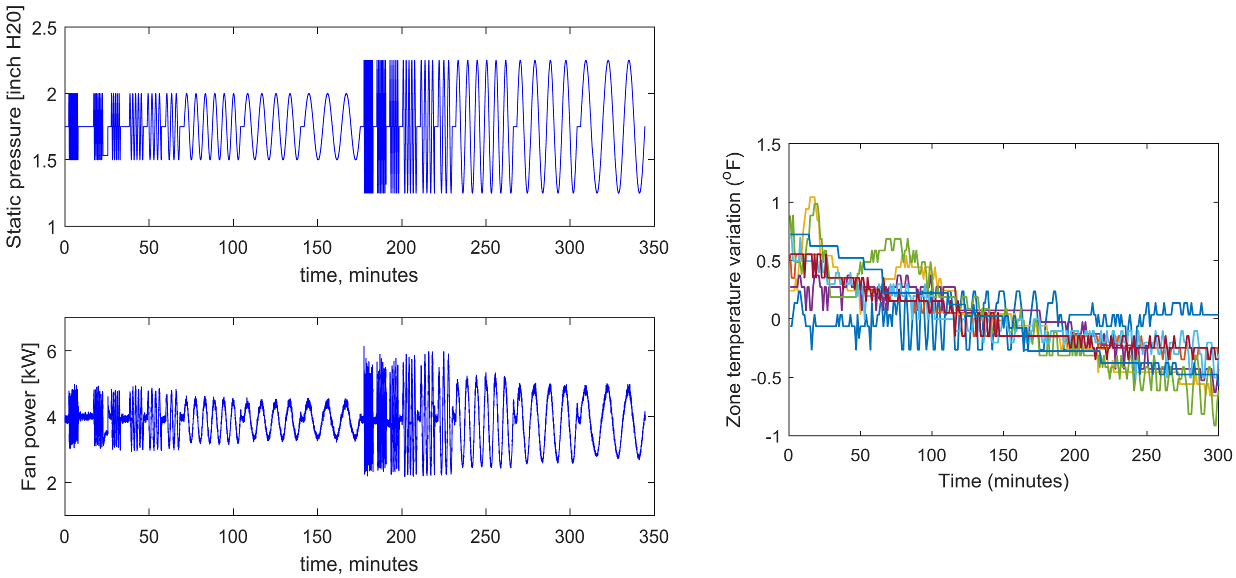

Figure 4: Left: Fan power response (bottom) to sinusoidal signals in static pressure set-point (top). Right: Variability in zone temperature during the frequency regulation experiment.

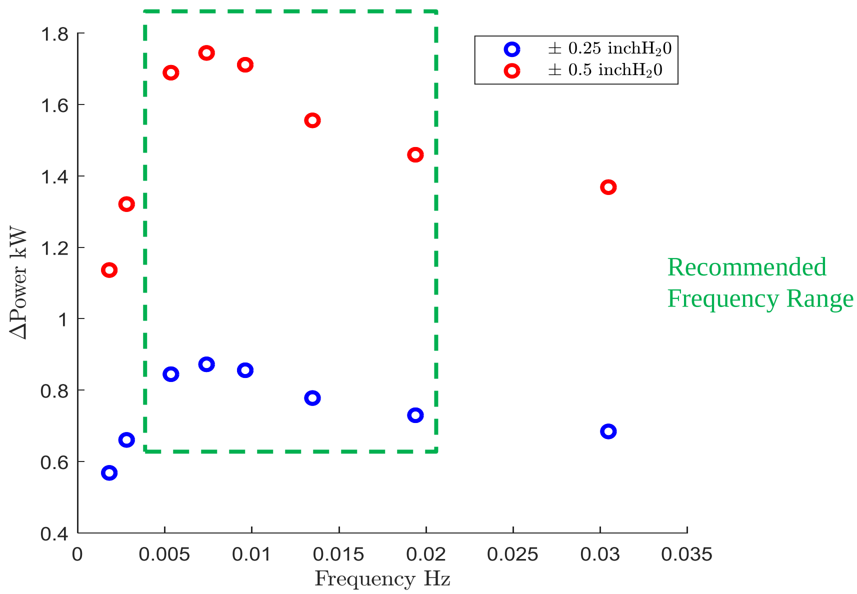

Figure 5: Frequency response plot of fan power response to sinusoidal changes in static pressure.

Table 3: AHU fan frequency regulation capability

	Requirement	**AHU fan**
Frequency range (Hz)	NA	[0.0055 , 0.022] Hz ([1/(3min) , 1/(45sec)])
Amplitude	NA	±1.7kW
Reserve magnitude (% load)	>5%	18.9% of rated power, (43% of nominal power)
Ramp time	<5 minutes	11.25 – 45 sec

3. FREQUENCY REGULATION CONTROL

In this section, we design the frequency regulation controller (FRC) whose bandwidth includes the frequency range identified in the quantification test. The proposed frequency regulation control changes the command to the AHU fan motor speed (and hence power consumption) by indirectly modifying the duct static pressure (DSP) set-point. This architecture is selected for its ease of implementation. It only requires a simple software add-on to the existing HVAC control system; the local fan speed and zone climate control loops remain the same.

3.1 Control Architecture

The architecture for the Frequency Regulation Control (FRC) is shown in Figure 6. The output of the FRC controller (ΔDSP spt) is added to the nominal set-point before it is passed to the existing baseline fan control logic. The FRC varies the fan power consumption so that the deviation from its baseline power profile (ΔPower) tracks the reference signal $\Delta\text{Power}^{\text{grid}}$. The resource controller has two main blocks: nominal power estimator and the reference tracking controller.

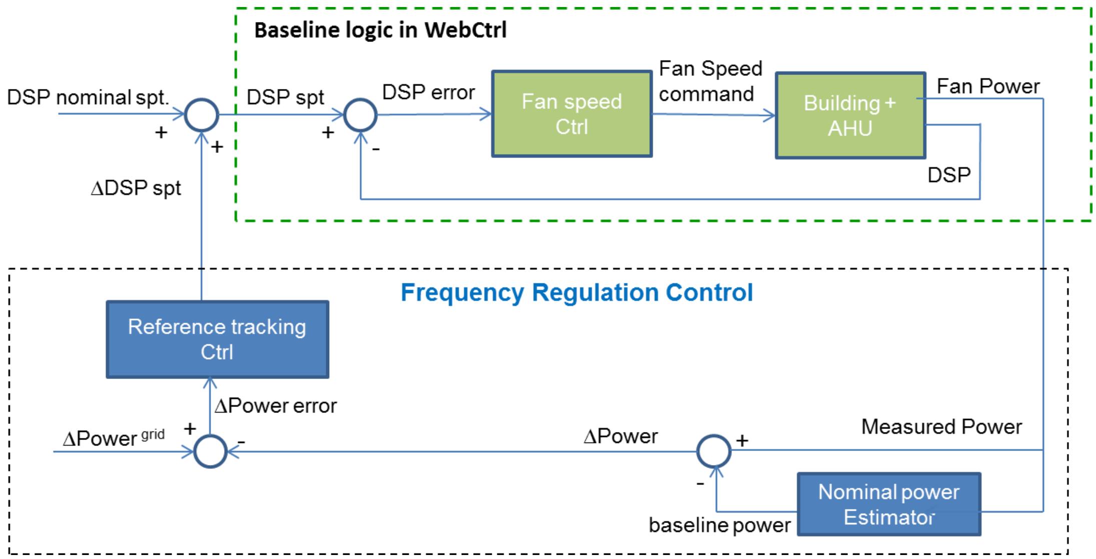

Figure 6: Frequency regulation control architecture

Nominal Power Estimator: This block estimates the power the resource would have consumed under a normal operating condition, without providing ancillary service. The nominal power can be estimated through machine learning, low pass filter (Lin *et al.*, 2015) or model-based constrained optimization (Hao *et al.*, 2017). In this study, the nominal estimator is a DSP-to-power data-driven model, identified as a second order transfer function based on the frequency response data generated in section 2.3.

Reference tracking controller: The tracking controller computes the required perturbation to the nominal DSP such that ΔPower (= Measured power – estimated nominal power) follows the reference grid power ($\Delta\text{Power}^{\text{grid}}$). The controller is a classic feedback controller that maximizes the tracking performance within the identified frequency range of interest ($f \in [0.0055\,,\ 0.022]H_z$) while minimizing the actuator effort.

4. EXPERIMENTAL RESULTS

The frequency regulation controller was implemented in Simulink and communicates with the UTRC building BAS through the WebCtrl server that is connected to the ALC controllers via BACnet over IP network. The set-up is shown in Figure 7. Prior to experimental testing, the FRC controller was validated in a simulation environment with almost perfect tracking.

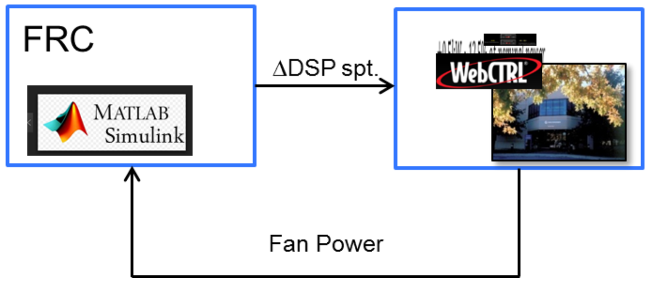

Figure 7: Experimental test set-up

PJM standard test regulation signals (RegD) were used to assess the FRC performance. The signal ramps up and down fairly quickly and is almost energy neutral (on average) over a period of time. Each experiment was conducted over a forty minute period to meet the test duration for both the NODES program (>30 minutes) and PJM qualification requirements. Figure 8 shows the controller performance while tracking three RegD signals. The reference signals were verified to lie within the HVAC flexible frequency range (otherwise they would need to be filtered) and were scaled to match the available frequency regulation power magnitude.

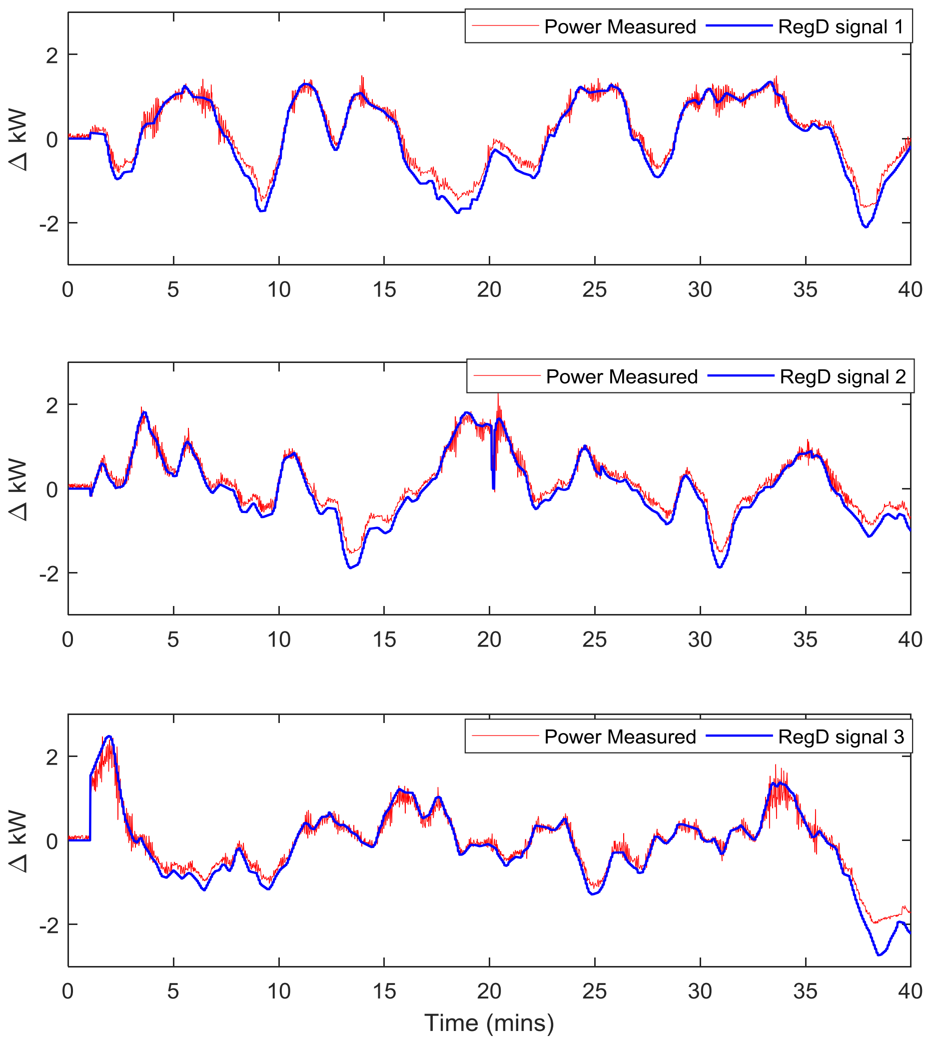

Figure 8: Experiment results for frequency regulation controller with three RegD reference signals

The controller performance was quantified using NODES metrics (Table 1), PJM performance metrics based on the formula provided in their manual (PJM 2017, pages 54-56) and the tracking error metric used by Lin *et al*. (2015):

$$r_R = \frac{\frac{1}{N}\sqrt{\sum_{j=1}^{N}\left(\Delta\text{Power}^{\text{grid}}(j) - \Delta\text{Power(j)}\right)^2}}{\max(|\Delta\text{Power}^{\text{grid}}|)} \tag{7}$$

The results show that the building HVAC FRC is consistently able to provide satisfactory grid support. The evaluation against NODES metrics is summarized in Table 4. We note that 1) the response times are less than 4 seconds, meeting the 5 second requirement, 2) the reserve magnitudes range from 29% to 44%, exceeding the 5% requirement, and 3) the ramping times are less than 60 seconds, well within the 5 minute requirement. While the 5% target for the Reserve Magnitude Variability Tolerance (RMVT) was met in a simulation environment, a degraded performance was obtained in the experiments partly due to the measurement noise and communication delay between the local computer used for the FRC and the building controls (Figure 7). The RMVT is calculated as the maximum variability between the regulation signal and actual power response over a five-minute window. The score is expected to improve by programming the FRC as EIKON Logic in WebCTRL and using data from the existing control system. The PJM scores are provided in Table 5. The composite scores (0.89, 0.96, and 0.78) exceed the PJM threshold of 0.75. The tracking errors using eqn. 7 are 0.10, 0.11 and 0.08 for regD signals 1 to 3 respectively. The results compare favorably with the 0.19 experimental value obtained in (Lin *et al*., 2015).

Table 4: Experimental results performance against NODES qualitative and quantitative requirements

Metric	**Target**	**RegD signal 1**	**RegD Signal 2**	**RegD Signal 3**
Response Time:	<5 sec	<4 sec	<4 sec	<4 sec
Reserve Mag. Target (% of nominal load)	>5%	29%	40%	44%
Reserve magnitude variability tolerance (RMVT)	< 5%	<16%	<18%	<15%
Ramp time	<5 mins	<60sec	<60 sec	<60sec
Duration	>30 mins	>30 mins	>30 mins	>30 mins
Availability	>95%	100%	100%	100%

Table 5: Experimental results performance against PJM Performance metrics

Test signal	**Correlation score**	**Delay score**	**Precision score**	**Composite (mean) performance score**
Reg D 1	0.98	0.99	0.78	0.92
Reg D 2	0.97	0.99	0.71	0.89
Reg D 3	0.94	0.99	0.73	0.89

5. DISCUSSION

This work demonstrates the feasibility of advanced building-to-grid services such as frequency regulation in operational commercial buildings. The proposed frequency regulation control is simple and can be easily retrofit in to existing building controls. Next steps include the implementation of the FRC on ALC controller and enhancement of the tracking controls to better capture the nonlinearity in the supply air fan. Additional work under this project is also addressing the ability to correctly predict the available flexibility a building can offer to the grid in the hours ahead. These combined capabilities will provide superior building services to aggregators and grid operations in support of the current transition to more renewable and intermittent energy sources underway in North America.

To fully commercialize these capabilities, more work is required to verify the efficiency loss when the building

HVAC systems are providing ancillary services. The deployment and market barriers will also need to be addressed. The low frequency ancillary services such as ramping require proper coordination between the building's thermal supply and demand in order to maintain reliable climate control while providing the grid services. These solutions must scale across the diversity of the existing building stock, which will be a key challenge for accurate flexibility estimation. The constraints of HVAC equipment to offering frequency regulating services needs to be fully understood. And finally, incentives and educational outreach to drive the broader adoption of these solutions need to be further developed.

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ACKNOWLEDGEMENT

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000700. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.