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Using HVAC Systems for Providing Power Grid Ancillary Services

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Laboratory Tests of HVAC Systems Providing Power Grid Ancillary Services

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ABSTRACT

Real-time power supply and demand balances are critical to ensure stable power frequency and quality power services. However, the growing integration of renewable energy increasingly challenges the power infrastructure because most of the renewable resources, e.g., solar and wind energy, are intermittent and difficult to predict. To meet the stringent power frequency requirements, more fast reacting frequency regulation resources are being brought online among which grid-level batteries are the dominant ones. Although batteries can provide fast and high quality regulation services, they suffer from high initial cost, high environmental impact and round-trip efficiency losses. When providing fast frequency regulation services, battery life span could be significantly reduced, leading to even higher cost per unit of frequency regulation service. Buildings consume more than 73% of the electricity in the US, offering significant regulation reserve for the power grid. Variable-speed air-conditioning systems are taking an increasing share of the market due to the higher efficiency requirements imposed by federal agencies. In addition to efficiency benefits, variable-speed cooling/heating systems are also perfectly suited for providing ancillary service as these units can modulate their power continuously over a wide range. Compared to batteries, HVAC systems have several advantages for frequency regulation: 1) in theory, they do not incur any round-trip efficiency loss; 2) the time response of an AC unit could be faster than a battery (especially compared to energy batteries with slower ramping rates and relatively larger capacities); 3) the existing regulation capacity of HVAC systems is significant and the implementation cost is marginal compared to installing grid-level batteries; 4) HVAC systems have smaller embodied carbon compared to batteries. This paper presents laboratory test results of a variable-speed heat pump for power frequency regulation. Regulation performances for both the traditional (slow) and dynamic (fast) regulation services are reported. The tested performance scores were above 0.97; the regulation performance even beats the average regulation performance of batteries. Preliminary economic analysis was also performed using historical wholesale electricity and regulation prices. The results show that the credit received for frequency regulation could offset up to 47% of the HVAC electricity cost under the tested conditions.

1. INTRODUCTION

Frequency regulation, as one of the various types of ancillary services, is designed to ensure instantaneous balance of power supply and demand and to maintain a stable grid frequency. The growing integration of renewable energy on the power grid increasingly challenges the power infrastructure, because most of the renewable resources, e.g., solar and wind energy, are intermittent and difficult to predict. To meet the stringent power frequency requirements, the grid has seen record demand for frequency regulation capacity, especially for fast regulation resources. Incorporating energy storage has been seen as the most effective technology to absorb the uncertainties in the renewable power generation, but cost is a major limiting factor for wide deployment of energy storage.

The Federal Energy Regulatory Commission (FERC) passed rules in recent years attempting to open the regulation markets to demand side resources and to establish monetary incentives for end users to participate in the regulation market. Frequency regulation requires demand side resources to vary their power use to follow an automatic generation control (AGC) signal that is generated based on real-time power supply and demand imbalance.

Participation in the regulation service could result in significant economic benefits for the building owners. For the power grid operation, deeper demand side participation could increase the total regulation capacity and allow more renewable integration on the gird.

Buildings account for more than 73% of the total electricity use in the US and more than one third of the electrical energy use in buildings is attributed to heating, ventilation and air conditioning (HVAC) systems (EIA, 2018). HVAC equipment links building thermal loads and the space cooling/heating electrical energy consumption. HVAC loads are perfectly suited for frequency regulation since the thermal inertia associated with HVAC and envelope construction materials can filter out the high frequency components in the electrical power modulation, leading to small impact on indoor temperature control when a building provides frequency regulation service. Variable-speed HVAC equipment has seen increased market share due to higher efficiency requirements imposed by federal agencies in recent years. Variable-speed HVAC systems offer significantly enhanced energy efficiency and also increase buildings' capacity for frequency regulation.

In recent years, researchers started to investigate the feasibility of using HVAC systems for power grid frequency regulation service. Most of the previous studies focused on parts or types of HVAC systems that are relatively straightforward to operate and analyze, such as fans and electrical heaters. For example, Lin et al. (2015), Vrettos et al. (2017), and MacDonald (2014) studied the feasibility of using air-distribution fans in commercial buildings for ancillary services; however, fans only contribute a small fraction of the instantaneous HVAC power. Fabietti et al. (2017) performed field tests using electrical space heaters to provide regulation service in a commercial building. Although the potential for power regulation of vapor-compression air conditioning and heat pumping units is much more significant because of their large power requirements and widespread application, the analysis and controller design for provision of ancillary services using vapor-compression systems are more difficult. Thus, fewer studies have been reported. Kim et al. (2016) carried out a laboratory test using a variable-speed heat pump to provide grid frequency regulation service. The supply water temperature setpoint was adjusted to modulate the heat pump power in an indirect manner and the reported performance scores are mostly less than 0.8. A number of studies (Blum and Norford, 2014; Zhao et al., 2013; Pavlak et al., 2014) relied on building simulation tools to analyze performance of whole HVAC systems for frequency regulation; however, quasi-steady-state HVAC models were predominantly used in these studies and the system dynamic performance during regulation control was not captured.

This paper presents laboratory test results of a variable-speed split heat pump for power frequency regulation. The unit was retrofitted with variable-speed drives installed on the compressor, indoor fan and condenser fan. Thus, direct speed control was available for all three component drives. A simple feedback control strategy was developed that monitors the total unit power and generates speed commands for the compressor and supply fan in a synchronized manner. Laboratory tests were carried out using the PJM (Pennsylvania-New Jersey-Maryland Interconnection, a regional transmission organization) traditional (RegA) and dynamic (RegD) test signals. Regulation performance was evaluated using the PJM performance score calculation engine. First-order economic analysis results for the test conditions are also reported using the PJM average whole-sale electricity and regulation prices for the year of 2015. A companion paper (Cai et al., 2018a) presents a similar study for a variable-speed rooftop unit whose component speeds are not directly controllable; the companion study is representative of an add-on control solution to enable the unit's frequency regulation capability. This paper, however, focuses on the evaluation of an approach that could be directly implemented as an OEM control solution in which the component speeds can be directly controlled for power modulation. Performance comparison between the two control solutions is briefly described.

2. REGULATION MARKET OVERVIEW

Figure 1 shows the seven ISO/RTO's in the US. Different markets have different requirements on the type of regulation resources (supply versus demand resources), minimum size of regulation capacity and power regulation directions (symmetric and asymmetric; prices are different for ramp-up and ramp-down services for asymmetric markets). Each market is operated with its own market clearing schemes (day-ahead, hour-ahead and real-time markets). Zhou et al. (2016) provided a comprehensive review of the ancillary service markets in the US.

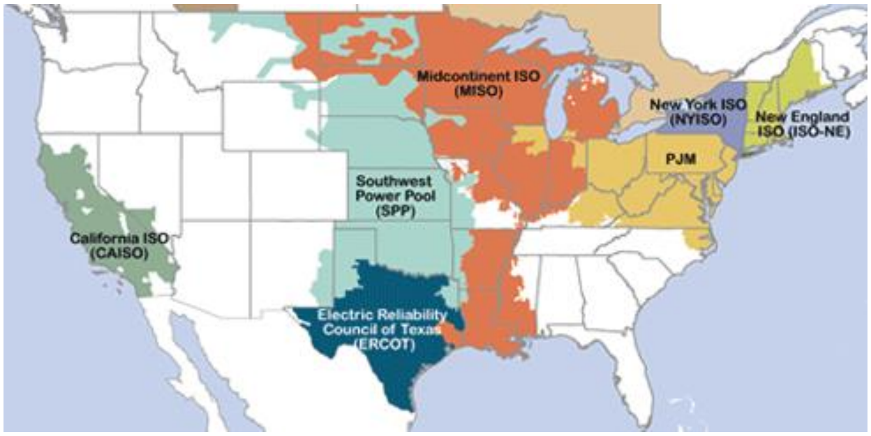

Figure 1. Seven ISO/RTO's in the US (source: FERC)

The PJM market is most favorable for demand-side regulation resources and thus, is used in this study to demonstrate the potential of using building HVAC systems for frequency regulation. The key characteristics of the PJM regulation market are:

- Minimum regulation capacity: 0.1 MW;
- Symmetric market, i.e., the ramp-up and ramp-down capacities need to be identical;
- Hour-ahead market;
- Demand-side resources are allowed.

2.1 Performance Scores

In compliance with FERC Order 755, the PJM market determines the regulation credit based on the regulation performance. PJM evaluates the performance for each service provider based on three sub-scores which characterize the accuracy, precision and delay performances, respectively. A composite score is an average of the three sub-scores. A minimum composite score of 0.75 is set forth by PJM for a resource to be eligible to bid in the market. The detailed calculation of each sub-score is given as follows.

For each 10-second time interval, a correlation score is calculated as the maximum correlation between the regulation signal and actual power response with time shifts from 0 to 5 minutes with a 10-second increment:

$$Correlation[t] = \max_{\sigma=0,10,\ldots,300(\text{sec})}\left(r(Reg[t:t+300], Res[t+\sigma:t+\sigma+300])\right).$$

where σ is the time lag, *Reg* the regulation signal generated by PJM, *Res* the actual unit power response and $x[t{:}t+300]$ the time series data within a 5-minute time period from time t. r calculates the Pearson correlation coefficient of the two time series:

$$r(X,Y) = \frac{\text{cov}(X,Y)}{\rho_X \rho_Y}$$

where cov is the covariance of the two time series and ρ is the standard deviation.

A delay δ is defined as the time at which the maximum correlation occurs, i.e.,

$$\delta = \arg\max_{\sigma=0,10,\ldots,300(\text{sec})}\left(r(Reg[t:t+300], Res[t+\sigma:t+\sigma+300])\right).$$

The instantaneous delay score is calculated as

$$Delay[t] = abs\left(\frac{\delta - 300(\text{sec})}{300(\text{sec})}\right).$$

Then the hourly delay and correlation scores are simply averages of the incident scores calculated above:

$$\text{Correlation Score} = mean(Correlation[:])$$

$$\text{Delay Score} = mean(Delay[:])$$

Define *Error* as the mean absolute of the relative errors between the regulation signal and power response:

$$Error = mean\left(abs\left(\frac{Res - Reg}{mean(Reg)}\right)\right)$$

Then the precision score is

$$\text{Precision Score} = 1 - \frac{1}{n}\sum abs(Error)$$

where n is the number of time steps in an hour or the evaluation period.

The accuracy or correlation score captures the statistical correlation between the regulation signal and actual power response. The delay score indicates the level of delay and the precision score represents the mean absolute error between the reference and actual unit power.

2.2 Regulation Mileage and Credit Accounting

PJM has two types of regulation services: traditional regulation service (called RegA) and dynamic regulation service (called RegD). RegA is designed for resources that have slow responses but large regulation capacities. RegD is a fast regulation service which requires the resources to follow an aggressively varying regulation signal. Regulation mileage is defined as the total distance the regulation signal traverses within a given period of time and is used to indicate how fast the regulation signal changes:

$$Mileage_{Reg} = \sum_{i=0}^{n} \left| Reg[i+1] - Reg[i] \right|$$

Since RegD is a fast regulation service, the RegD mileage is typically much higher than the RegA signal. A regulation resource will receive two credits from PJM, associated with the regulation capacity and the regulation performance, respectively. The detailed credit calculation is

$$\text{Capacity Credit} = RegCap \times PerformanceScore \times CapacityPrice$$
$$\text{Performance Credit} = RegCap \times PerformanceScore \times PerformancePrice \times MileageRatio$$
$$\text{Total Credit} = CapacityCredit + PerformanceCredit$$

where *RegCap* is the regulation capacity (kW), *MileageRatio* is the ratio of the participated service mileage to average RegA mileage, and *CapacityPrice* and *PerformancePrice* are the market clearing prices for the capacity and performance credits ($/kW per hour of service), respectively. Fast regulation service involves higher performance credits attributed to higher mileage ratios. Service with higher performance scores will result in higher monetary incentives for both the capacity and performance credits.

3. EXPERIMENTAL SETUP

3.1 Psychrometric Chamber

The heat pump unit was installed and tested in psychrometric chambers with a schematic given in Figure 2. The indoor and outdoor units were placed in the indoor and outdoor chambers, respectively. The regulation tests were carried out with constant chamber temperature and humidity to eliminate the impact of the operating conditions on the test performance. A comprehensive set of sensors was added to the test unit to provide detailed air-side and refrigerant-side measurements. Three power meters were installed to collect real-time power data for the condenser fan, supply fan and compressor.

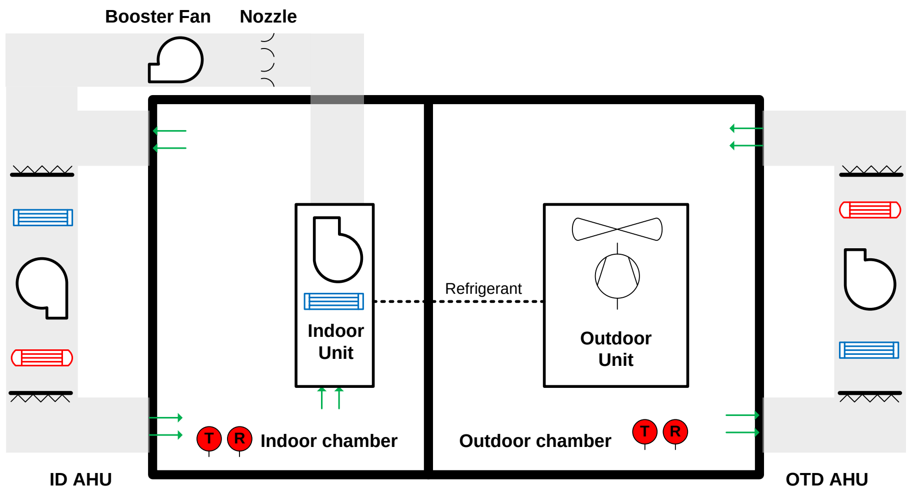

Figure 2. Psychrometric chamber and testing rig

3.2 Variable-Speed Heat Pump Instrumentation

Figure 3 shows the variable-speed split heat pump that was set up for the frequency regulation tests. The unit was originally single-staged with constant compressor and fan speeds. Variable-speed drives were added to the compressor, indoor and outdoor fans as an after-market retrofit. Individual component speed was directly controlled via an automation control unit (ACU) that converts a 0 to 10Vdc control signal to a pulse modulation width (PMW) signal for the drive. Three ACUs were installed to adjust speeds of the compressor, indoor fan and condenser fan, separately.

Figure 3. Variable-speed split heat pump setup for frequency regulation testing

In the tests, condenser fan speed was fixed at 100% since the condenser fan contributes a small fraction of the total unit power. Compressor and indoor fan speeds were adjusted continuously to vary the total unit power; the following constraints were considered in the speed control:

- compressor speed modulation range: 30% ~ 70%
- indoor fan speed modulation range: 35% ~ 100%

The maximum compressor speed was only 70% of full speed because the added compressor drive has a built-in logic that locks the unit operation at full speed whenever the compressor speed control command is above 70%. The regulation capacity loss due to the lockout logic could be recovered if a better control scheme can be developed that uses continuous fan power modulation to fill in the compressor power gap in the lockout mode. However, since this lockout logic is specific to this unit and not widely used in other heat pumps, this study did not further investigate the capacity recover control. The economic benefits evaluated and presented in this paper are lower than those associated with other variable-speed equipment when compressor speed can be varied over a larger range.

A single proportional-integral (PI) controller was implemented that monitors the total unit power and adjusts the compressor and indoor fan speeds in a synchronized way to track the power regulation signal provided by the ISO or RTO. The PI controller outputs a continuous control command from 0 to 100% which is then scaled to respective operation ranges and used as control commands for compressor and indoor fan speeds. In the PJM market, a regulation command is sent to regulation resources every two seconds; the time step in the PI control was set to two seconds.

4. TEST RESULTS

4.1 RegA Results

RegA is a traditional regulation service that assigns a slowly varying regulation signal for resources to follow. A 40-min RegA test signal was downloaded from the PJM website (http://www.pjm.com/markets-and-operations/ancillary-services.aspx) and was used in the regulation tests. Prior to the regulation tests, preliminary experiments were carried out with the unit to identify the regulation power upper and lower bounds associated with the maximum and minimum compressor and fan speeds. For the tested indoor and outdoor conditions, the highest and lowest unit power obtained were 3040W and 1240W, which resulted in a reference power level of 2140W (average of the upper and lower power bounds) and a regulation capacity of 900W. In an actual regulation control implementation, the regulation capacity and power bounds should be dynamically reset when building loads and other operating conditions change.

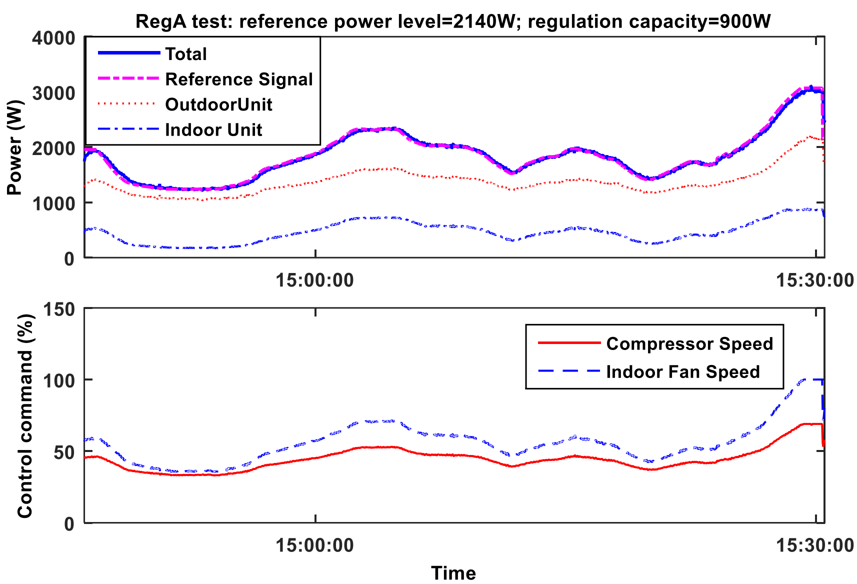

Figure 4. Heat pump RegA test: variations of unit power and control commands

Figure 4 shows the RegA test results, including the regulation reference signal, unit power responses and control commands. It can be seen that the unit can accurately respond to and track the regulation signal. Figure 5 shows the performance results calculated using the PJM performance score engine. The different subplots show the performance sub-scores evaluated at 5-min rolling time windows. Table 1 gives the detailed performance scores along with the regulation mileage. The split heat pump can provide high quality RegA service with a composite performance score of 0.98.

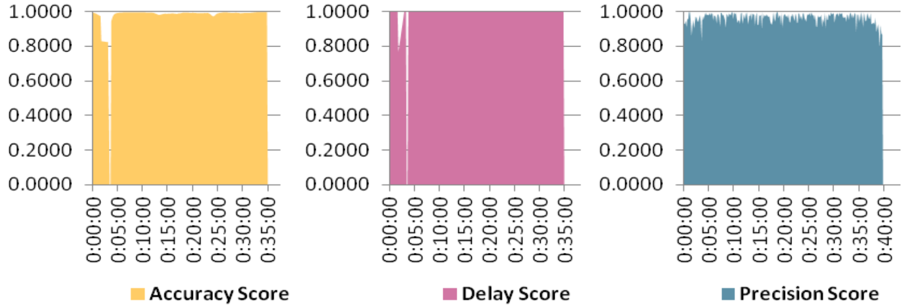

Figure 5. Heat pump RegA test performance

4.2 RegD Results

RegD is a fast regulation service that involves a much faster power regulation requirement compared to the RegA service. A RegD test was performed with the same setting as for the RegA test. Figure 6 shows the RegD test results. It can be observed that the RegD regulation signal changes at a much faster rate which is also reflected in the calculated mileage as shown in Table 1; the RegD regulation signal has a mileage three times greater compared to the RegA signal. Because of the dynamic power modulation required in the RegD service, minor delays are present in the unit power response and the precision score is slightly lower (0.92) than the other sub-scores. However, the overall tracking performance is still excellent with a composite performance score of 0.97.

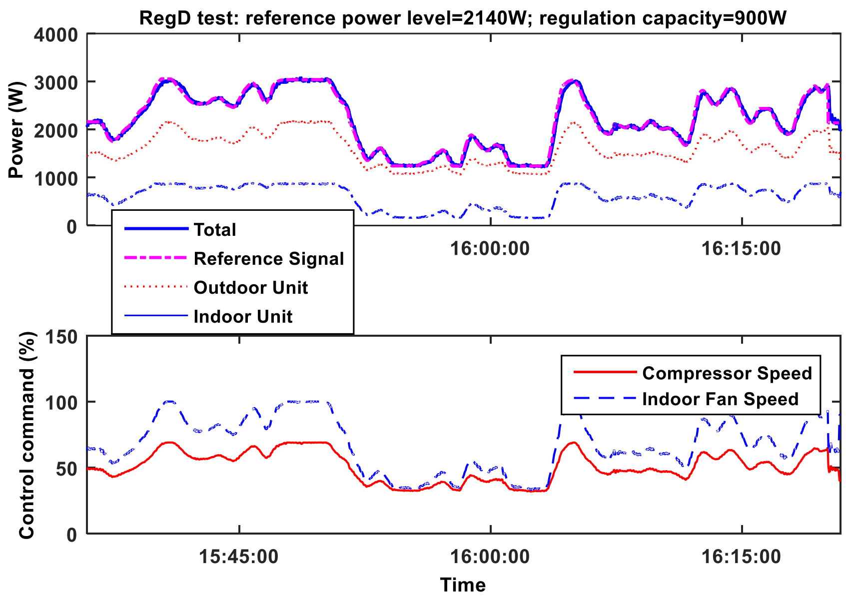

Figure 6. Heat pump RegD test: variations of unit power and control commands

Figure 7 gives the performance results evaluated for this RegD test and Table 1 gives the calculated performance scores. This RegD test has lower precision score than the RegA test leading to a slightly lower composite score. It is more difficult for the unit to track a RegD regulation signal due to the faster variation in the reference signal.

A companion paper (Cai et al., 2018) presents a similar experimental study with a variable-speed rooftop unit (RTU) whose component speeds are not directly controllable; the compressor speed was indirectly controlled by adjusting the supply air temperature setpoint. The presented RTU control represents an add-on control solution that can be utilized for existing variable-speed products to enable frequency regulation control. Due to lack of direct speed control, the tested performance scores were slightly lower (0.91 for RegA test and 0.95 for RegD test) compared to the regulation scores achieved with the heat pump unit, which is more representative of an OEM control solution with direct control access for all components.

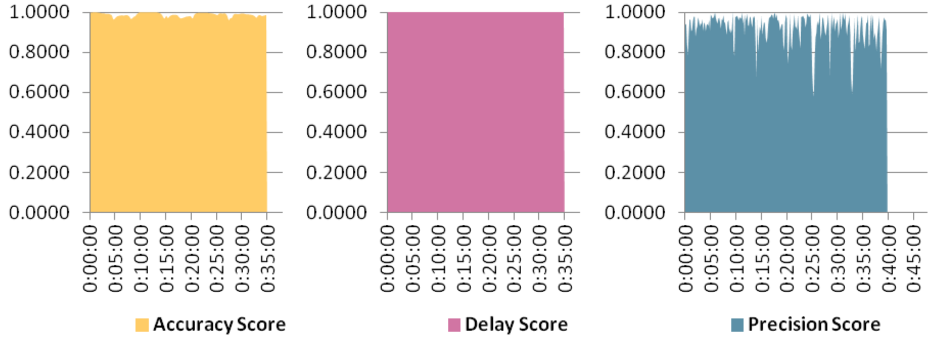

Figure 7. Heat pump RegD test performance

Table 1. Performance scores of the regulation tests

	Accuracy Score	Delay Score	Precision Score	Composite Score	Hourly Mileage
RegA	0.974	0.986	0.968	0.976	6.8
RegD	0.986	1	0.923	0.969	19.21

5. FIRST-ORDER ECONOMIC ANALYSIS

Building owners receive credits and economic benefits from ISO/RTOs for participation in the regulation market. Quantifying the economic benefits could help building owners better appreciate this building-grid integration opportunity. For system operators, economic analysis results also provide valuable information to better understand the demand-side participation in the frequency regulation market which could help better structure/plan the regulation resources. A first-order economic analysis was carried out to evaluate the utility savings potential associated with building regulation service. Historical PJM wholesale electricity (day-ahead) and regulation prices for 2015 were downloaded from the PJM website: http://www.pjm.com/markets-and-operations/ancillaryservices.aspx.

Annual average prices of 2015 were used to estimate the electricity cost to operate the test unit and the credits that could be received associated with the RegA and RegD tests presented above. Details of the PJM credit calculation method is given in Section 2. The economic analysis results are given in Table 2 for the specific test conditions. It was shown in Table 1 that RegD service involves much higher mileage, which is close to 3 times the RegA mileage, and the performance credit is proportional to the regulation mileage for given regulation capacity and performance. The economic analysis results given in Table 2 show that the RegD service could result in a credit that offsets 47% of the electricity cost. The estimated credit for the RegA test is slightly lower due to the smaller mileage, but is still close to 40% of the electricity cost. These results demonstrate the significant economic savings potential for buildings to participate in the frequency regulation market.

Table 2. First-order estimate of economic benefits for the regulation tests

	Electricity cost	Credit for RegA service	Credit for RegD service
Absolute cost/credit	7.3 cents/hr (1.82 cents/ton-hr)	2.8 cents/hr (0.7 cents/ton-hr)	3.4 cents/hr (0.85 cents/ton-hr)
Percentage of credit relative to cost	-	38.4%	47%

6. CONCLUSIONS & DISCUSSIONS

This paper presented a laboratory-based evaluation of using HVAC systems for providing power grid ancillary services. A 4-ton split heat pump with after-market variable-speed drives was tested in psychrometric chambers with PJM regulation test signals. A simple feedback control scheme was proposed that modulates the compressor and supply fan speeds in a synchronized manner to vary the unit power consumption in order to follow the regulation reference signal. The test results have shown that HVAC systems could provide high-quality frequency regulation ancillary service. Almost a perfect performance score (0.98) was achieved for the RegA service. For the faster RegD service, a slightly lower performance score (0.97) was obtained due to the aggressive variation in the regulation signal. To understand the economic benefits associated with HVAC frequency regulation control, a first-order economic analysis was performed for the tested conditions using 2015 PJM average electricity and regulation prices. The results show that the regulation credit can offset 47% of the hourly electricity cost for RegD service. The cost savings potential for RegA service (38.4%) is slightly lower than the RegD service due to a smaller mileage and lower performance credit.

Batteries are getting popular as regulation resources on the power grid due to their fast response. There are a number of grid-level battery projects that have just been completed or are under development in the US, mainly targeted for the frequency regulation market. HVAC systems can outperform batteries for frequency regulation in several aspects. The reported performance scores that can be achieved with HVAC systems are higher than the average performance associated with batteries (see Figure 8 for the performance comparison with batteries and other regulation resources on the grid). Almost all buildings have HVAC systems installed; the cost (mostly control and metering system upgrade) to bring them online is marginal compared to installing grid-level batteries. Also, batteries are notorious for round-trip efficiency losses, fast capacity degradation with aggressive charging/discharging strategies and significant environmental impact in the manufacturing phase. Although a few studies (Beil et al., 2015 and Lin et al., 2016) reported round-trip efficiency losses when buildings were used for frequency regulation, a more rigorous experimental study (Cai and Braun, 2018b) has shown that frequency regulation control has negligible impact on energy efficiency for HVAC systems. For humid climate locations, regulation control could improve the sensible cooling efficiency due to reduced latent load. Future work will quantify the impact of regulation control on equipment life time; the impact is believed to be smaller compared to the life cycle impact for batteries.

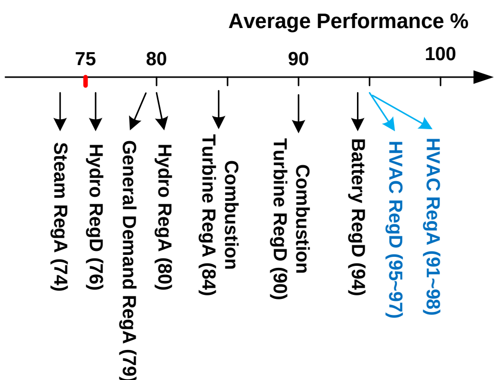

Figure 8. Performance comparison with other regulation resources on the power grid.

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REFERENCES

Beil, I., I. A. Hiskens, and S. Backhaus, "Round-trip efficiency of fast demand response in a large commercial air conditioner," Energy and Buildings, vol. 97, pp. 47–55, Jun. 2015.

Blum, D.H., Norford, L.K., 2014. Dynamic simulation and analysis of ancillary service demand response strategies for variable air volume HVAC systems. HVAC&R Research 20, 908–921.

Cai, J., Lin, Y., and Braun, J.E., "Laboratory Demonstration of Variable-Speed Packaged Air-Conditioning Units for Provision of Frequency Regulation Services", IEEE Conference on Innovative Smart Grid Technologies, 2018a.

Cai, J. and Braun, J.E., “Laboratory-Based Assessment of HVAC Systems for Provision of Power Frequency Regulation Service: Regulation Performance, Economic Benefits and Efficiency Impact”, in preparation, 2018b.

Energy Information Administration, "Annual Energy Review", URL: https://www.eia.gov/totalenergy/data/annual/index.php, accessed Feb 2018.

Fabietti, L., T. Gorecki, F. Qureshi, A. Bitlislioglu, I. Lymperopoulos, and C. Jones, “Experimental Implementation of Frequency Regulation Services Using Commercial Buildings,” IEEE Transactions on Smart Grid, vol. PP, no. 99, pp. 1–1, 2017.

Kim, Y. J., E. Fuentes, and L. K. Norford, “Experimental Study of Grid Frequency Regulation Ancillary Service of a Variable Speed Heat Pump,” IEEE Transactions on Power Systems, vol. 31, no. 4, pp. 3090–3099, Jul. 2016.

Lin, Y., P. Barooah, S. Meyn, and T. Middelkoop, “Experimental Evaluation of Frequency Regulation From Commercial Building HVAC Systems,” IEEE Transactions on Smart Grid, vol. 6, no. 2, pp. 776–783, Mar. 2015.

Lin, Y., J. L. Mathieu, J. X. Johnson, I. A. Hiskens, and S. Backhaus, “Explaining Inefficiencies in Buildings Providing Ancillary Services,” in Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, 2016.

Lin, Y., P. Barooah, and J. L. Mathieu, “Ancillary Services Through Demand Scheduling and Control of Commercial Buildings,” IEEE Transactions on Power Systems, vol. 32, no. 1, pp. 186–197, Jan. 2017.

MacDonald, J., “Commercial Building Loads Providing Ancillary Services in PJM,” eScholarship, Aug. 2014.

Pavlak GS, Henze GP, Cushing VJ. Optimizing commercial building participation in energy and ancillary service markets. Energy and Buildings. 2014 Oct 1;81:115-26.

PJM Regulation Self Test Signals, URL: http://www.pjm.com/markets-and-operations/ancillary-services.aspx.

Vrettos, E., E. C. Kara, J. MacDonald, G. Andersson, and D. S. Callaway, “Experimental Demonstration of Frequency Regulation by Commercial Buildings: Part I: Modeling and Hierarchical Control Design,” IEEE Transactions on Smart Grid, vol. PP, no. 99, pp. 1–1, 2017.

Zhao, P., G. P. Henze, S. Plamp, and V. J. Cushing, “Evaluation of commercial building HVAC systems as frequency regulation providers,” Energy and Buildings, vol. 67, pp. 225–235, Dec. 2013.

Zhou Z, Levin T, Conzelmann G. Survey of US ancillary services markets. Argonne National Lab.(ANL), Argonne, IL (United States); 2016 Jan 1.