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Advanced HVAC System for Smart Grid

March 2015

S Whalen
C Corbin

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Executive Summary

Rocky Research (Boulder City, NV) has developed an advanced roof top air conditioning unit (RTU) with the potential for providing smart grid functions such as regulation services and PV integration. The RTU contains advanced technologies that have been demonstrated to enable 1) improved coefficient of performance (COP) during start-up transients, 2) improved steady-state efficiency, and 3) blending of DC and AC power with high conversion efficiency. Technologies incorporated by Rocky Research include a pulsing thermal expansion valve (PTXV) to dynamically optimize refrigerant flow, a variable frequency drive (VFD) for the compressor, and on-board integrated power conversion electronics for inverting and blending DC and AC power.

A 3-ton Carrier RTU underwent baseline testing to characterize COP with an indoor temperature of 80°F and outdoor temperatures of 95°F and 110°F. The modulating thermal expansion valve was then replaced with Rocky Research's PTXV, a VFD was added to the compressor, and DC-AC power electronics were included. Baseline testing was repeated, and the following improvements were measured that are relevant for short time-scale (i.e., <10min) smart grid applications, such as frequency regulation and fast-acting ancillary services for renewable balancing.

- ≈10-15% increase in max steady state COP
- ≈26% reduction in time to reach max COP
- >90% DC to AC conversion efficiency

PNNL then performed a GridLAB-D analysis to determine the impact of frequency regulation on energy consumption for a population of RTUs outfitted with, and without, PTXV and VFD. Simulations show that energy consumption was ~4% lower for RTUs containing PTXV and VFD compared to stock RTUs during frequency regulation (i.e., more frequent cycling).

Acknowledgments

We thank William Parks and Dan Ton from the Department of Energy (DOE) Office of Electricity (OE) for supporting this collaboration between the Pacific Northwest National Laboratory (PNNL) and Rocky Research.

Acronyms and Abbreviations

AB	As-Built
AC	Alternating Current
CBECS	Commercial Building Energy Consumption Survey
COP	Coefficient of Performance
DC	Direct Current
DOE	Department of Energy
FOV	Fixed Orifice Valve
MPPT	Maximum Power Point Tracking
OE	Office of Electricity
PJM	Pennsylvania New Jersey Maryland Interconnection LLC
PNNL	Pacific Northwest National Laboratory
PTXV	Pulsing Thermal Expansion Valve
PV	Photovoltaic
RTU	Roof Top Air Conditioning Unit
SEER	Seasonal Energy Efficiency Ratio
TXV	Thermal Expansion Valve
VDC	DC Voltage
VFD	Variable Frequency Drive
ZVS	Zero Voltage Switching

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1.0 Introduction

Air conditioners draw a considerable fraction of the total power consumed by residential and commercial buildings [1, 2]. As such, air conditioners have the potential to play an important role in providing demand response for grid services such as frequency regulation and fast-acting (minutes) ancillary services. However, these services require more frequent cycling, which can reduce overall efficiency due to a degraded coefficient of performance (COP) during start-up transients. Developing technology that reduces this detrimental effect on COP during start-up will be an important part of demand response solutions for these grid services. To this end, Rocky Research integrated pulsing thermal expansion valve technology (PTXV) [3] into a roof top air conditioning unit (RTU) that improves efficiency by reducing the time required to reach steady-state COP during start-up.

As roof top photovoltaic (PV) systems find further penetration into the commercial buildings market, there is an opportunity to integrate renewable energy directly with co-located RTUs. The advantage is that RTUs with on-board inverters and power electronics could result in more efficient, cost-effective, and reliable building cooling systems using solar power directly. As a first step toward realizing these advantages, Rocky Research upgraded an RTU with a local inverter, a variable speed drive (VFD), and power electronics that seamlessly blend AC and DC power.

Although a single RTU's response is likely not capable of matching a frequency regulation signal, a population of RTUs acting in concert may be able to provide regulation services. Using data collected by Rocky Research for the advanced RTU, PNNL performed a simulation, using GridLAB-D, to investigate at a very high-level the ability of advanced RTUs to perform regulation service as a population [4].

This report briefly summarizes the work performed by Rocky Research and PNNL on advanced RTUs.

2.0 Advanced RTU Development

2.1 Baseline Testing

Two 3-ton Carrier RTUs (Model 50ES-A36: SEER 13 shown in Figure 1) [5] were procured by Rocky Research along with all associated hardware and subsystems. The RTUs were installed within an environmental chamber and instrumented per ASHRAE standard methods for airflow and temperature measurements (Figure 2). Both RTUs underwent baseline testing with the indoor air temperature held constant at 80°F and the outside temperature regulated at 95°F and 110°F. Cooling capacity and power consumption were measured as a function of time, from off to steady-state, and the results were within ~5% of the manufacturers' published information. Baseline testing was repeated over the course of several days to establish repeatability and confidence in the data. Results show that the COP for Unit 1 was ~2-3% higher on average than Unit 2, due to slightly different refrigerant charge as received from the manufacturer.

Figure 1. 3-Ton Carrier RTU Procured by Rocky Research for Advanced RTU Project

Figure 2. Instrumented RTU Installed in Environmental Chamber and Undergoing Baseline Testing

2.2 Testing with PTXV

A shortfall of modulating thermal expansion (TXV) and fixed orifice valves (FOV) found in today's RTUs is that they do not precisely control the refrigerant flow under changing conditions. Response adjusts slowly in the case of TXV, and not at all in the case of FOV. In addition, the capillary between the condenser and evaporator is only optimized for a single design point. As such, the overall refrigerant control system is not optimized when the evaporator temperature, condenser temperature, refrigerant mass flow, or pressure deviate from a very narrow design point where steady-state SEER testing is performed.

Figure 3. Rocky Research PTXV Installed on Carrier 50ES-A36 RTU as a Replacement to the Stock TXV

In this task, Rocky Research replaced the stock TXV, shown in Figure 3, with a custom designed PTXV with a configuration and connective tubing optimized for the Carrier model 50ES-A36 RTU. The PTXV gives much finer control over the refrigerant flow by dynamically (and passively) optimizing the refrigerant flow between the condenser and evaporator in real time. As such, the PTXV optimizes refrigerant flow over a broader range of conditions, resulting in improved efficiency, both during the start-up transient and during steady-state operation. The baseline tests were repeated with the PTXV and upgraded distribution installed.

Figure 4 compares COP and time for the baseline Unit 1 (**blue**) and Unit 1 modified with the PTXV (**red**) tested with an inside temperature of 80°F and outside temperature of 95°F. Replacing the stock TXV with a PTXV and optimizing tubing size results in a ≈11% increase in max COP and ≈26% reduction in the time required to reach max COP. Testing with an outside temperature of 110°F resulted in slightly less improvement (a few % lower) than at 95°F. Increases in COP measured during the start-up transient (i.e., first ≈10 minutes) are due to the ability of the PTXV, and upgraded distribution system, to dynamically optimize refrigerant flow even though temperature and pressure conditions are changing quickly. In this comparison, little benefit is seen below one minute but a difference of ≈15% is achieved between minutes one and three. We hypothesize that these improvements during start-up may increase the capability of RTUs to provide demand response for regulation services. The improvement in steady-state COP is attributed to the PTXV being able to optimize refrigerant flow for the specific test conditions.

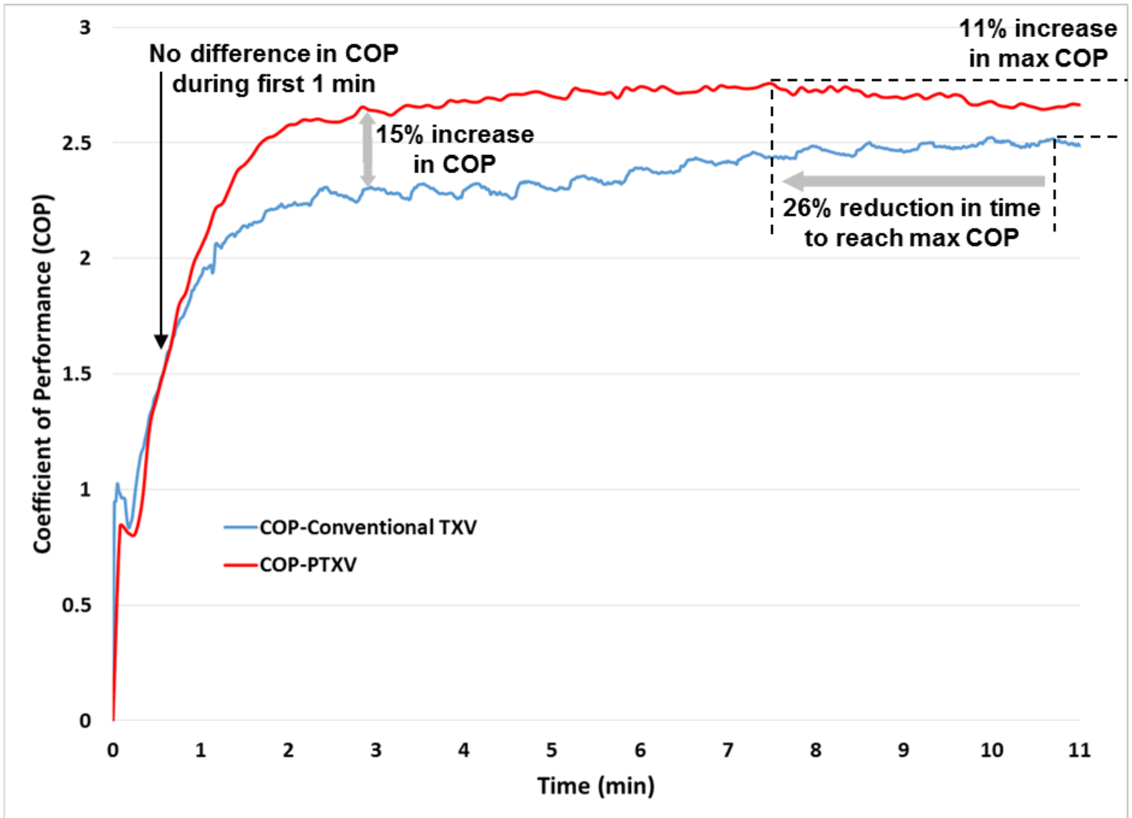

Figure 4. Comparison of RTU with Stock TXV and New PTXV Showing an 11% Improvement in Max COP and 26% Reduction in Time to Max COP. The largest rate in deviation of COP occurs between one and three minutes.

2.3 AC-DC Power Electronics and Variable Speed Drive

Rocky Research modified Unit 1, with the PTXV installed, to also include 1) custom power inverter electronics that allow for blending of AC and DC power and 2) a variable speed drive on the compressor. With these additions, the RTU is more adaptable to integration of DC renewable resources, such as PV, or DC energy storage, such as batteries. Such an RTU is advantageous where renewable energy is co-located, such as roof top PV, and when renewables or batteries cannot provide all of the power needed to run the RTU and supplemental AC power is required.

The grid-tie inverter is designed to convert a 400-450 VDC input into 3-phase AC power and is tightly packaged within the RTU as shown in Figure 5 and Figure 6. The inverter utilizes state-of-the-art resonant circuit zero-voltage switching (ZVS) to achieve high quality AC power output with a DC to AC efficiency greater than 90%. High power quality prevents interference with other equipment connected to the same electrical system. For PV arrays, a systems level approach for achieving the highest power from each solar panel is called Maximum Power Point Tracking (MPPT). With MPPT, each panel has a DC/DC boost converter that feeds a 400 VDC bus that could be directly connected to the RTU through the grid-tie inverter.

Figure 5. Location of Power Electronics Integrated with RTU

Figure 6. Power Electronics Integrated with RTU Below Cooling Fan

Some advantages of distributing power inverters at the RTU level compared to a large central inverter at the PV array level (i.e., for roof top PV) are as follows:

- *Matching inverter size to load*: By distributing power electronics to the RTU level, the size of the inverter is exactly matched to the size of the load. This is not possible with a single inverter at the array level (sold in large discrete intervals) and can lead to reduced overall cost per kW for the power conversion electronics.
- *Higher efficiency*: Conversion efficiency of >90% at small scale using state-of-the-art resonant ZVS efficiency. This exceeds the capability of commercial inverters of a scale compatible with roof top PV.
- *Improved uptime & serviceability*: If the inverter fails in a central inverter, the entire system stops producing power and recovery is typically slow. By comparison, an inverter failure in a single RTU that is part of a parallel string of RTUs will only reduce cooling capacity by the amount of one RTU. In contrast, all cooling would cease if the central inverter went down.

Testing of the custom RTU power electronics show that DC to AC conversion occurs at >90%, and that blending of AC and DC power can be accomplished for any fraction of DC power ranging from 0 to

100%. In addition, testing with the variable speed drive shows an additional 5% gain in maximum steady-state COP when the outside temperature was 95°F (Figure 7). This increase is attributed to the VFD being programmed for the existing scroll compressor specifications. The VFD was tested at different compressor speeds from 100% down to 60% of full speed, along with different combinations of AC and DC inputs. The VFD and power electronics conversion efficiencies were both measured to be >90%.

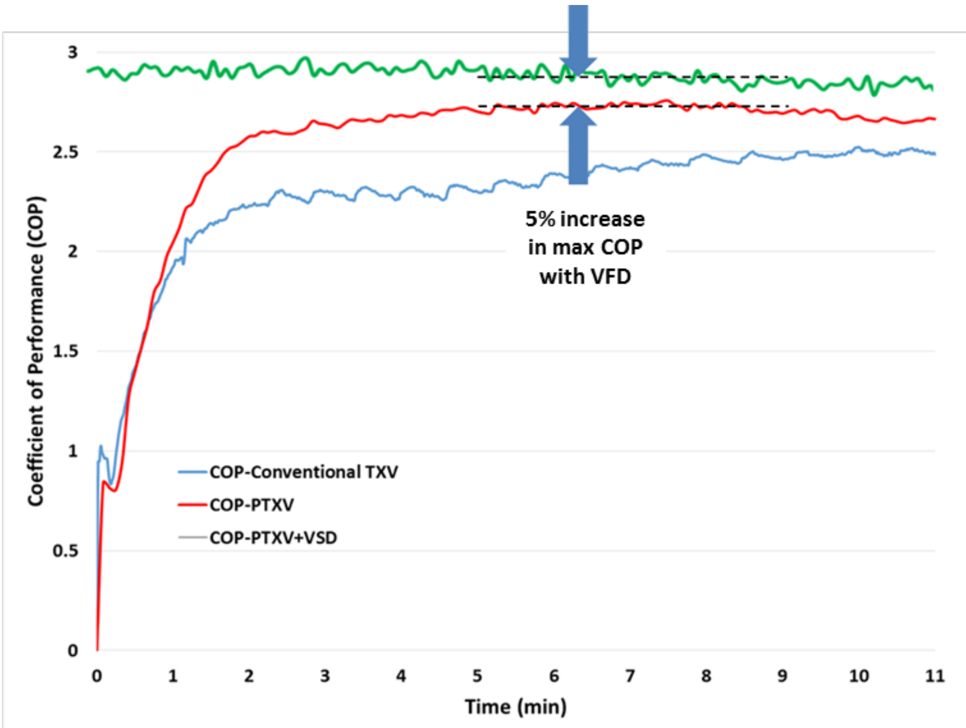

Figure 7. Comparison of RTU with VFD+PTXV and PTXV Only Showing a 5% Improvement in Max Steady-State COP

Figure 8 shows that a ~5% increase in COP is achieved by decreasing the VFD speed slightly, from 60Hz (e.g., 100%) down to 56Hz (e.g., 93%). This is because cooling capacity remains essentially unchanged, while the power consumption drops by ~5%.

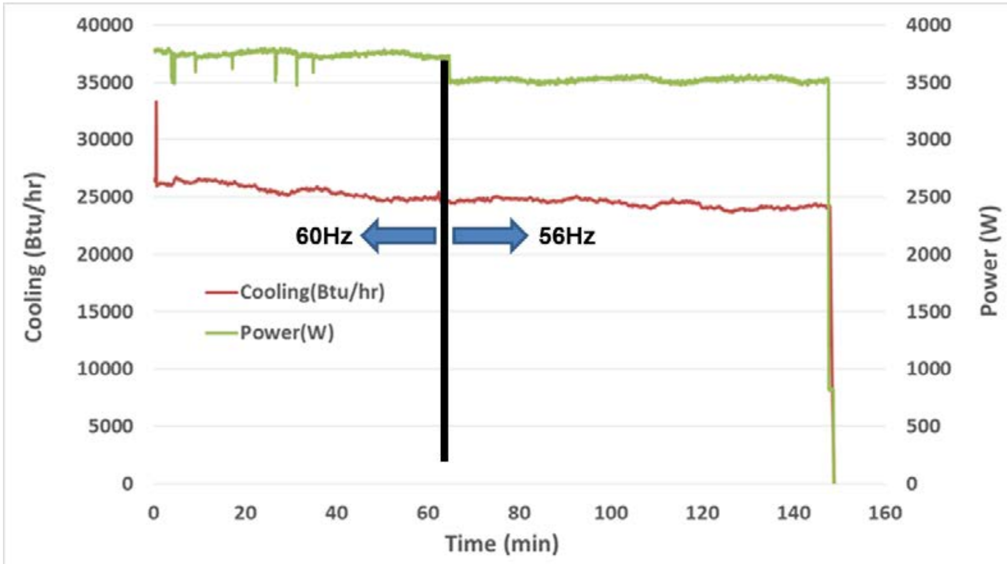

Figure 8. Effect of Partial Load on Capacity Showing 5% Decrease in Power Consumption with Little Decrease in Capacity

3.0 Simulation of Advanced RTU Population Performing Regulation Service

This study investigated the energy performance impact of frequency regulation on a population of RTUs outfitted with and without PTXV and VFD, using computer simulation models incorporating the measured transient performance characteristics of the units. A comparison was performed between the Rocky Research technology and an as-built stock unit (AB), using a modified version of the GridLAB-D software package.

The study was designed to answer two primary questions:

- What effect does frequency regulation have on energy consumption of the RTUs?
- What do the shape of performance curves contribute to the previous result?

3.1 Method

Capacity, power, and COP data from the as-built RTU and RTU with PTXV were used to generate capacity and COP curves characterizing the transient behavior of the tested units. Because the compressor model in GridLAB-D is fairly simple, these curves were characterized only by the unit's time spent in a cooling cycle.

GridLAB-D was then modified to utilize these curves when simulating the performance of the RTUs. Nominal COPs were adjusted up from the measured values for both the AB and PTXV units to account for motor energy, which is simulated separately in GridLAB-D, but combined with the compressor in the measured data.

Simulated COP, cooling, and power curves were compared with measured data to validate model performance. Examples of cooling and power curve fits can be seen in Figure 9 and Figure 10. Normalized root mean squared error between simulated curves and measured data indicated excellent agreement.

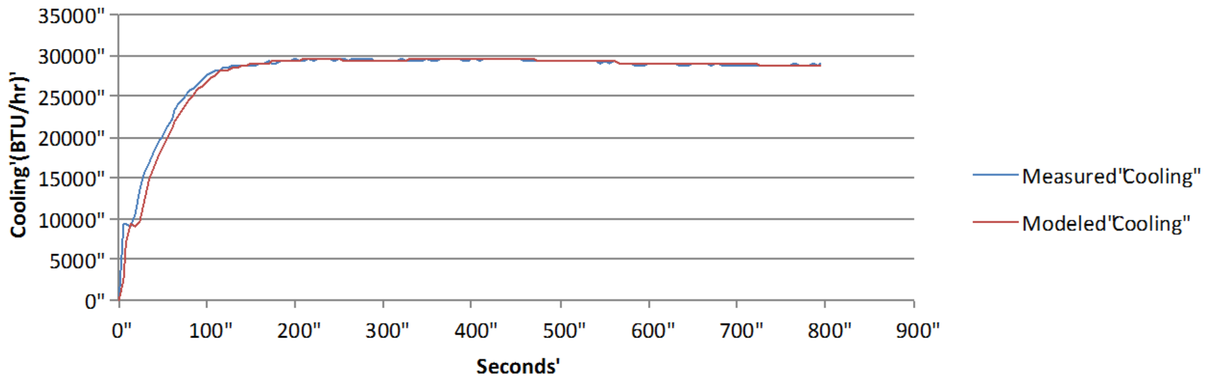

Figure 9. Cooling Curve Fit for PTXV Model and Data

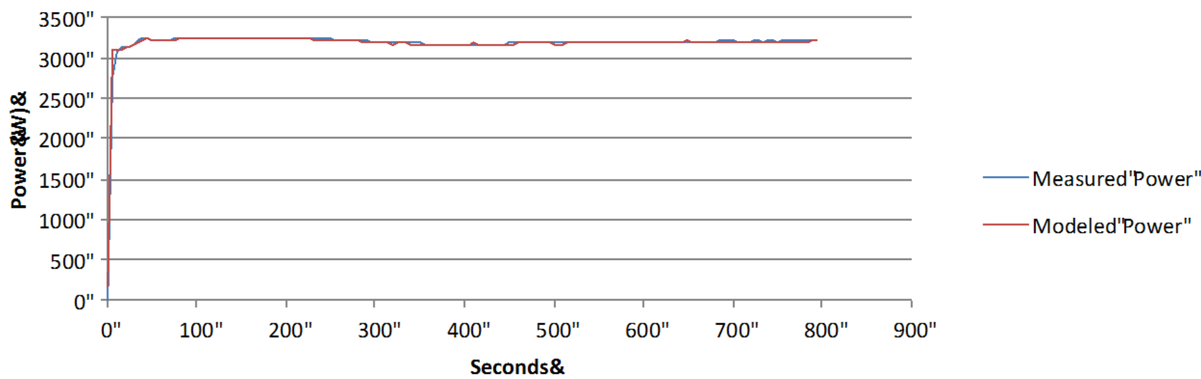

Figure 10. Power Curve Fit for PTVX Model and Data

In addition to developing curve fits, linear regression was used to relate steady-state capacity and COP to operating speed from the PTXV unit under two operating speeds. The regression coefficients were coded into GridLAB-D to allow simulation of a VFD on the compressor.

3.2 Population Model

A GridLAB-D model consisting of 200 five-zone buildings was constructed using a diversity of envelope characteristics and floor areas. Zone floor area averaged 2,000 sq. ft. Lighting, equipment, and occupant densities were derived from Commercial Building Energy CBECS. Each zone was provided with an RTU, and each RTU was provided a controller that could respond to a frequency regulation signal.

3.3 Simulation Cases

The population of buildings was simulated for a single day, July 1, using typical weather from Newark, NJ. A fast frequency regulation signal (reg-D), as observed in the Pennsylvania New Jersey Maryland Interconnection LLC (PJM) market during July 1, 2009, was provided to the controllers to invoke a response from the RTUs. Several different controller strategies were employed to produce a range of responses.

The controllers in each RTU were configured to provide proportional control to one or more variables using the regulation signal as input. Cases included: A) cooling set point deviations of up to +/- 1ºF; B) cooling set point deviations of up to +/- 2ºF; C) cooling set point dead band down to 0.1ºF and up to 3.9ºF; D) drive frequencies down to 35Hz and up to 60Hz; E) combination of A and D; F) combination of B and D; G) minimum cycle times down to 0 sec and up to 240 sec.

3.4 Results

All strategies caused units to cycle more frequently, but only if they had exceeded the minimum cycle time. An individual unit's ability to follow a fast regulation signal was thus limited by minimum cycle length, which was lowered to two minutes from the default five minutes in these simulations. In the case of strategy G, the dead band was reduced to 0.05ºF to encourage very rapid cycling. In practice, cycle times this short may cause increased wear and premature failure of the unit.

In cases D, E, and F, greater response fidelity was possible within the range of allowable drive frequencies. However, if conditions dictated, the unit with the VFD was still subject to cycling if drive speed was driven below 35Hz.

As a population, the control strategies resulted in differing degrees of response to the frequency regulation signal. The strategy showing the greatest ability to respond to the regulation signal, case F, combined cooling temperature set point deviations of +/- 2ºF, with VFD speeds down to 35Hz. Figure 11 shows the frequency signal and population response between the hours of noon and 6:00 pm for this case. Note that the population response is measured relative to a simulation of similar buildings without a frequency responsive controller.

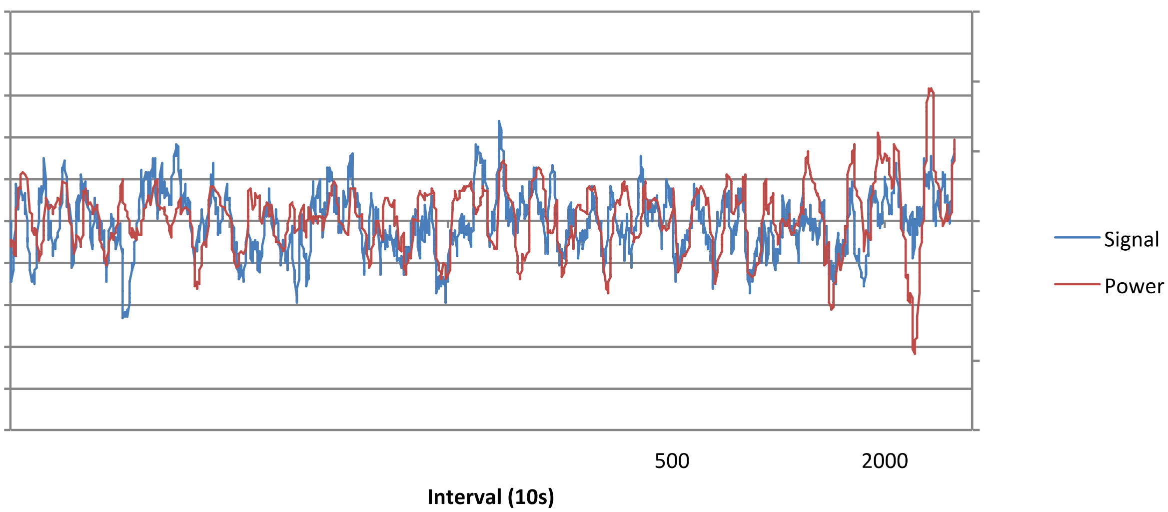

Figure 11. Power Response of RTU Population Driven by Regulation Signal

The population was not capable of following the regulation signal perfectly, sometimes demanding greater power when the regulation signal request is lower, and vice-versa. This was due to the limitations imposed by comfort constraints. During several periods, a large percentage of the population was observed to increase demand concurrently to satisfy the cooling load, regardless of what the overall electrical system required. Alternative strategies in which compressor operation is manipulated directly may allow more responsiveness, but may lead to comfort violations; this method was not explored.

When comparing energy consumption during the noon to 6:00 pm window, increases were observed in all regulation cases for the AB unit, as shown in Table 1. This is the result of more frequent cycling, and thus more time spent at a lower average COP. In case D, although COP increased at lower speeds, the increased cycling observed below 35Hz outweighed the benefit. For case G, cycling was observed to increase by an order of magnitude, and the increase in electric consumption was much more marked. In all PTXV cases, the same trend was observed, despite a global reduction in electricity consumption.

Table 1. Difference in Electricity Consumption in Frequency Regulation Cases

	As-Built	PTXV
No Control	0.00%	-3.67%
Case A: Cooling Set Point +/- 1°F	0.35%	-3.35%
Case B: Cooling Set Point +/- 2°F	0.49%	-3.24%
Case C: Deadband	0.25%	-3.42%
Case D: VFD	0.09%	-3.59%
Case E: VFD & Cooling Set Point +/- 1°F	0.24%	-3.45%
Case F: VFD & Cooling Set Point +/- 2°F	0.39%	-3.33%
Case G: Cycle Time	2.07%	-1.96%

A second set of simulations was performed (Table 2) to separate the effect of the increased COP from the transient performance characteristics. In one group of simulations, only the performance curve of the PTXV unit was used, keeping the COP the same as the AB unit (see PTXV Curve in Table 2). In another, only the nominal COP was increased to the PTXV value, keeping the performance curve of the AB unit (see PTXV COP in Table 2). The results indicate that the energy consumption benefit of the PTXV unit comes from the increase in COP, not the difference in transient behavior. In fact, the simulation suggests that the transient behavior, taken alone, would result in an increase in electricity consumption.

Table 2. Effect of COP and Transients on Electricity Consumption in Frequency Regulation Cases

	As-Built	PTXV Curve	PTXV COP
No Control	0.00%	0.99%	-4.57%
Case A: Cooling Set Point +/- 1°F	0.35%	1.33%	-4.24%
Case B: Cooling Set Point +/- 2°F	0.49%	1.44%	-4.11%
Case C: Deadband	0.25%	1.24%	-4.34%
Case D: VFD	0.09%	1.06%	-4.48%
Case E: VFD & Cooling Set Point +/- 1°F	0.24%	1.21%	-4.34%
Case F: VFD & Cooling Set Point +/- 2°F	0.39%	1.34%	-4.20%
Case G: Cycle Time	2.07%	2.83%	-2.66%

3.5 Conclusion

Simulations of a large population of RTUs, incorporating the Rocky Research PTXV technology, suggested that energy could be saved compared to off-the-shelf units. Furthermore, when the PTXV units were subjected to controls providing frequency regulation services, the losses associated with more frequent equipment cycling were not as large as those observed in the AB cases. The transient performance characteristics of the technology did not appear to contribute to a reduction in energy consumption. The reduction in electricity consumption in the PTXV units was attributed to the overall increase in COP that the technology provided.

4.0 References

[1] "Residnetial Energy Consumption Survey (RECS)," U.S. Energy Information Administration, 2009.

[2] "Commercial Buildings Energy Consumption Survey (CBECS)," U.S. Energy Information Administration, 2012.

[3] K. Khalili, C. Spangler, A. Schultz, "High Efficiency Variable Speed Versatile Power Air Conditioning System for Military Vehicles," NDIA Ground Vehicle Systems Engineering and Technology Symposium, Troy, MI, Aug. 21-22, 2012.

[4] J. Fuller, B. Vyakaranam, N. Kumar, S. Leistritz, G. Parker, "Modeling of GE Appliances in GRidLAB-D: Peak Demand Reduction," PNNL-21358, Apr., 2012.

[5] http://dms.hvacpartners.com/docs/1009/public/0b/50es-08pd.pdf. Accessed on 3-13-2015.

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