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Laboratory Assessment of a Demand Response Controller for Rooftop Units

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ABSTRACT

A major factor affecting the electrical power demand requirements of the air conditioners is the ambient dry-bulb temperature (DBT). Past studies show air conditioners need more power and energy when operating during hot weather, and thereby increase power demand during summer peak energy use periods. The integration of renewable energy, from wind and solar technology, with the electric grid is expected to change the way grid works, including a redefinition of “peak periods” from mid-day to late afternoon. To balance demand and capacity for sustaining grid reliability, utilities offer their customers economic incentives to reduced electricity consumption through demand response (DR) programs. Recognizing the importance of power demand reductions, a laboratory research project is initiated to explore the DR potential and human comfort effects of installing a retrofit controller on a 5-ton rooftop unit (RTU). This paper presents the project findings. The evaluated controller was capable of responding to two distinct DR signals: “moderate” and “high.” Based on the signal, the controller limited RTU’s power demand by modulating the frequency or speed of the compressor and indoor fan. Eight tests were conducted, accounting for variations in indoor and outdoor conditions, as well as the DR event notification types. The outdoor conditions represented air conditioners rating point and elevated climatic setting. The indoor conditions characterized a typical temperature setting with moderate humidity level, and a typical air conditioner rating condition with high humidity level. Results verified controller’s consistent response to the activated DR signals. The implemented DR strategies established the demand reduction potential of up to 60% for the RTU. The outcome of demand-limiting strategies, however, was an alarmingly elevated indoor DBT, indicating to move away from traditional mindset of sacrificing human comfort at peak outdoor conditions to reduce grid demand. Future studies should consider evaluating control technologies with different strategies, and under a 24-hour dynamic load profile following upcoming test standards for DR-capable devices. As the industry continues to explore DR solutions that offer potential for reducing power and energy demand for air conditioners, findings from this project will contribute to the body of knowledge and add value to future research by empirically substantiating advantages and drawbacks associated with control strategies.

1. INTRODUCTION

Residential and commercial unitary air conditioners are one of the major sources of the growing electrical energy use and peak power demand in California (Buntine *et al*., 2008). For instance, in 2006, residential air conditioners accounted for 24% of the peak power demand (Hunt *et al*., 2010). According to California Commercial End-Use Survey (2006), the electricity usage of air conditioning systems in commercial sector was 29%. A large percentage of the air conditioners found in California's small- or light-commercial sector are packaged rooftop units (RTUs), with cooling capacities ranging between five- and ten-tons. One of the most common air conditioning units within this capacity range is a five-ton packaged RTU (Faramarzi *et al*., 2004).

The electrical power demand and energy usage of air conditioners that are equipped with air-cooled condensers varies based on the outdoor or ambient dry-bulb temperatures (DBTs). Figure 1 shows the total power demand of five 5-ton RTUs as a function of outdoor DBTs from previous research. As shown in Figure 1, the power demand of all five RTUs increased as the outdoor DBT increased from 85°F to 125°F.

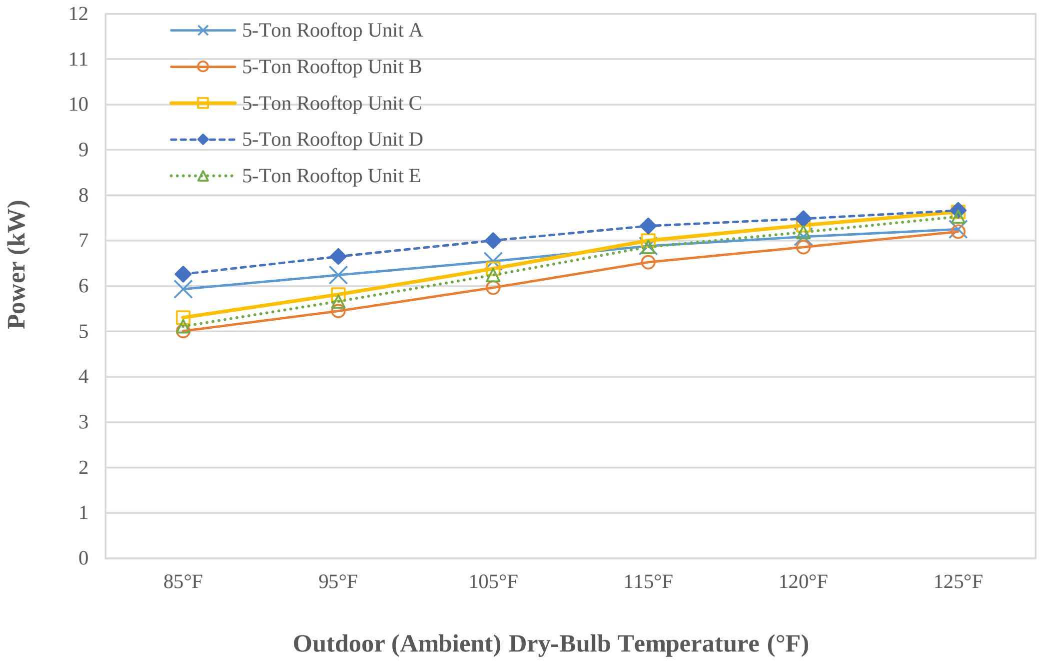


Figure 1: Total power usage profile of five 5-ton rooftop units as a function of outdoor dry-bulb temperatures

Further, the largest contributor to the total power of an air conditioner is the compressor, as illustrated in Figure 2. Since the compressor contributes over 80% of the total power of a RTU (Figure 2), technologies that can reduce compressor power, and subsequently energy usage, are beneficial for reducing overall power and energy of RTUs, when needed.

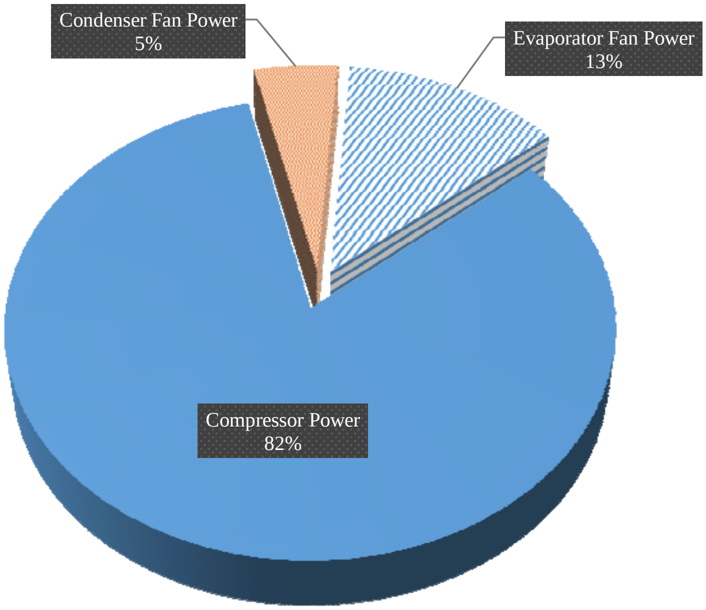


Figure 2: Percentage breakdown of power usage by main components of a rooftop unit
[averaged based on five 5-ton rooftop units at six outdoor dry-bulb temperatures ranging from 85°F to 125°F]

Traditionally, the increased power demand of air conditioners during summer peak mid-day hours has contributed to grid failures due to lack of adequate electricity generation. However, at least in California, it is anticipated that as the power generated from renewables (solar in particular) increases, the electricity demand profile will change from the traditional peak mid-day hours to the early and late evening hours (Alstone *et al.*, 2016). That is, the increase in solar power flowing into the grid during mid-day hours will drop net demand, or load. As solar starts to diminish in the late afternoon and into the evening, however, a sharp increase in net demand will occur when people arrive home and start using electricity. This characterizes a distinctive duck-shaped curve (Alstone *et al.*, 2016).

The traditional summer peak mid-day demand, or over-generation of renewables during peak ambient conditions that shift the demand to the late afternoon, can have an adverse impact on electric grid reliability. To sustain grid integrity by balancing demand and capacity, utilities offer their customers economic demand response (DR) program incentives to reduce electricity usage at certain times of the day. The DR programs are essentially services and resources that provide an opportunity to reduce and manage their electricity consumption at certain periods of day, while receiving economic benefits. Obviously, DR programs vary by region and utility, depending on when they provide the most value to the grid. For example, considering a future electricity demand profile as a duck curve, for air conditioners two types of DR services are proposed: “shift” and “shimmy.” As its name implies, shift DR services will encourage shifting the energy usage from one period to another. Shimmy is envisioned as fast DR services operating on a short time scale, based on variability of net load (Alstone *et al.*, 2017).

To communicate DR event notifications and establish connectivity with the electric end-use devices, in recent years, utilities adopted using Open Automated Demand Response (OpenADR) internet messaging protocol. To take full advantage of DR programs, though, consumers need access to equipment and appliances that allow communications of rate and grid conditions, and offer integrated control capabilities to respond to the information received. Such DR capabilities can be achieved either at the factory level or by retrofitting and installing add-on devices to existing equipment.

The objective of the research project described here is to promote DR solutions in air conditioning applications. The project attempts to establish potential power demand reductions of a RTU during DR events, and capture the impact of DR strategies on indoor DBT through laboratory testing and analysis. This paper discusses results of experimental evaluation of an add-on retrofit controller with DR capabilities on a nominal 5-ton RTU.

A series of tests were performed on a 5-ton RTU after installing the retrofit controller technology in controlled-environment test chambers. The evaluation captured key data points for the RTU operating under two sets of indoor and outdoor DBTs, before and after initiating DR events. This enabled tight control and maintenance of key test parameters. After data collection was complete, the RTU's performance data from before and after each DR event was compared. This allowed evaluating the response of the technology to DR signals, quantifying the power demand reductions, and quantifying the impact on indoor DBT for each test scenario.

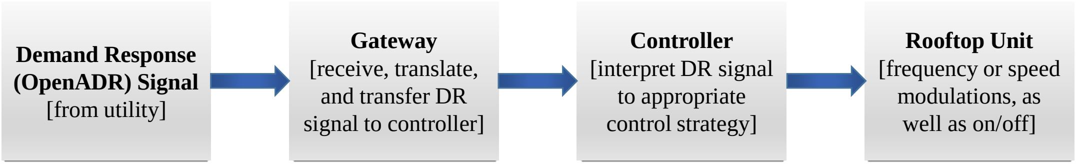
2. TECHNOLOGY DESCRIPTION

The evaluated technology in this project is a retrofit variable frequency drive (VFD) controller with embedded DR strategies designed for commercial air conditioners. The manufacturer of the controller has chosen to modulate the frequency or speed of the indoor fan and compressor only, not the condenser fan. This controller was installed on a nominal 5-ton standard efficiency heat pump RTU. The RTU uses R-410A refrigerant, a single-phase scroll type compressor, and thermostatic expansion valves for both indoor and outdoor coils. Even though the controller was installed on a heat pump unit, this study primarily focused on the unit's cooling-mode operation.

Typically, to connect and communicate DR event signals with the controller, a bridge device is required to take the DR signal from the utility and translate it to the controller. The bridge device could be a building management or automation system, a communicating thermostat, or a gateway. In this project, the DR event notifications were communicated with the controller using a gateway device. Figure 3 illustrates the communication path. As illustrated, the gateway device receives the OpenADR signal, then it translates and passes that information to the controller to perform the pre-programmed demand limiting strategies, according to the message.

In addition, since the VFD controller was capable of modulating the speed of a three-phase compressor, the original single-phase compressor was replaced with a three-phase unit with the same cooling capacity. Under normal operations, the controller modulates the frequency (hence speed) of the air conditioner's compressor and indoor fan simultaneously, according to the cooling load or thermostat setting. As part of the DR strategy, however, the controller varies the speed of the compressor and indoor fan according to the DR signal. This particular controller was pre-programmed with strategies to respond to two distinct moderate and high DR events. The controller's DR strategies for moderate and high event signals are:

- Moderate event: reduce the frequency of the compressor and indoor fan to 42 Hertz (Hz) and below.
- High event: run the compressor and indoor fan at 40Hz for nine minutes, then shut off the compressor for six minutes. When the compressor is off, run the indoor fan at 20Hz.



Demand Response (OpenADR) Signal [from utility]

Gateway [receive, translate, and transfer DR signal to controller]

Controller [interpret DR signal to appropriate control strategy]

Rooftop Unit [frequency or speed modulations, as well as on/off]

Figure 3: Communication path between the demand response signal, gateway, controller, and the rooftop unit

3. TEST METHODOLOGY AND SETUP

For all tests, the cooling capacities and performance characteristics were determined with guidance from the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 210/240-2008, and Standard 37-2009 developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Instrumentations were installed at locations required by these test standards. The air- and refrigerant-enthalpy methods set by the test standards were followed, to measure air and refrigerant properties. An airflow measurement apparatus, as specified by ASHRAE protocols, was used to measure the volumetric airflow rates across the evaporator coil.

To measure the refrigerant mass flow rate, a coriolis mass flow meter was installed in the liquid line. Electric power instrumentations were installed to measure compressor, condenser fan, evaporator fan, and total power input to the unit. The air and refrigerant properties, flow rates, and total input power data were used to obtain cooling capacities. Further, indoor and outdoor DBTs and wet-bulb temperatures (WBTs) were measured and monitored to ensure key test parameters were maintained. The data acquisition system was set up to scan and log 79 data channels in 20-second intervals. The test setup uses a two-chamber configuration for the indoor and outdoor areas. Figure 4, not to scale, depicts the top view of the indoor and outdoor test chambers with the RTU.

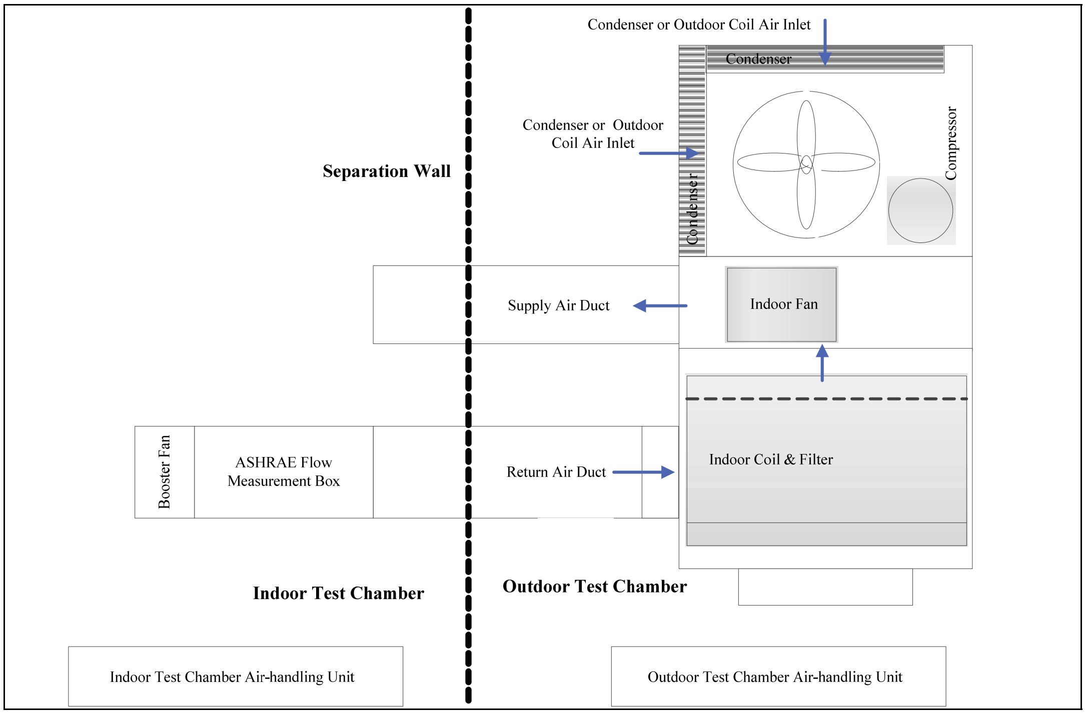


Figure 4: Schematics of two-chamber test configuration – top view, not to scale

4. TEST SCENARIOS

A set of eight tests was designed to compare the performance of the RTU during normal operations and during DR events. The tests were run for high and moderate event DR signal types. These tests were done for the following two sets of indoor conditions, at outdoor DBTs of 95°F and 105°F:

- Set 1: DBT of 75°F and WBT of 63°F, to characterize a typical temperature setting with a moderate humidity level. This is very close to indoor design conditions of 75°F DBT and 50% relative humidity specified in Manual J of Air Conditioning Contractors of America.
- Set 2: DBT of 80°F and WBT of 67°F, to replicate AHRI’s rating conditions with high humidity.

Table 1 summarizes all test scenarios, which were run for the typical DR duration of 60 minutes. To ensure the unit operates at full capacity, the imposed cooling load for test runs with DBT of 75°F and WBT of 63°F was kept at 4.2-ton, while for test runs with DBT of 95°F and WBT of 67°F, it was kept at 4.5-ton. The indoor test chamber’s air-handling unit (electric heaters) and humidifiers provided the sensible and latent loads needed for maintaining target indoor conditions. The outdoor test chamber’s air-handling unit provided the sensible loads needed for maintaining target outdoor conditions.

Table 1: Test scenarios

Indoor Conditions	Outdoor DBT	DR Signal Type	DR Event Duration	Imposed Cooling Load
Indoor DBT of 75°F and WBT of 63°F	95°F	Moderate	60 minutes	4.2-ton
		High		
	105°F	Moderate		
		High		
Indoor DBT of 80°F and WBT of 67°F	95°F	Moderate	60 minutes	4.5-ton
		High		
	105°F	Moderate		
		High		

4. TEST RESTULS

4.1 Key test control parameters

Three essential test control parameters were indoor DBT and WBT, as well as outdoor DBT. Figure 5 shows the average values recorded for each parameter prior to initiation of the DR event for all eight test scenarios. As shown, indoor and outdoor temperatures were maintained at desired levels for each test. This enhanced confidence in the results.

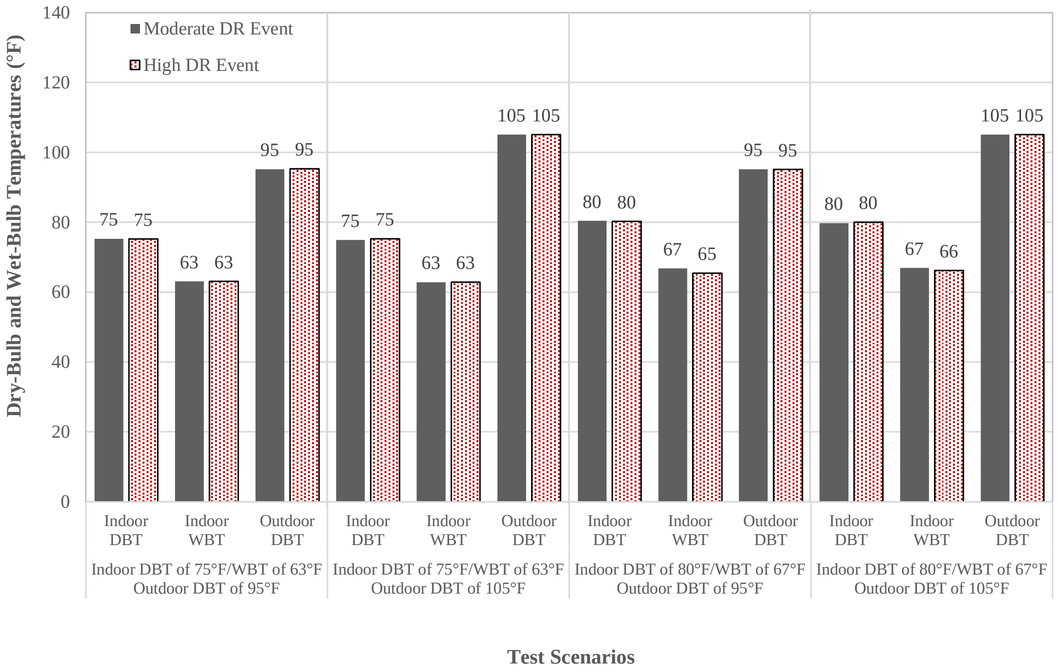


Figure 5: Key control parameters for all test runs

4.2 Representative power profiles

The power profile response under each DR event type was similar, despite minor variations in the magnitude due to different outdoor DBTs. This confirmed the controller's consistency in responding to each of the two DR event types. Therefore, to exemplify and be concise, the 20-second sampling power data for moderate and high DR events for a single indoor and outdoor condition are presented and discussed in this section.

Figure 6 depicts the 20-second-sampling power data profiles before, during, and after a moderate DR event for the indoor DBT of 75°F and WBT of 63°F, at an outdoor DBT of 105°F. The power profiles are for indoor fan, condenser (or outdoor) fan, compressor, and total unit. The DR event duration was 60 minutes, and it is marked in Figure 6. Clearly, the compressor was the main contributor to total power. Prior to and after the DR event (normal operations) the unit was running at full speed, or 60Hz, with an average total power of 6.0 kilowatts (kW). When the DR event was initiated, the frequency was dropped to 42Hz and stayed there until the end of the event, as intended. As depicted in Figure 6, during the DR event, the compressor and indoor fan power was reduced simultaneously. Consequently, the average total power during the DR event was 4.8 kW. In other words, during the event, the average total power was dropped from 6.0 kW to 4.8 kW, which was a 20% reduction in power.

Further, reducing the compressor speed inherently caused a drop in refrigerant mass flow rate, and thereby cooling capacity of the unit. The average cooling capacity during normal operation was 48,756 British thermal unit per hour (Btu/hr), or 4.1 ton. During the DR event, however, it was dropped to 42,246 Btu/hr or 3.5 ton, corresponding to a 13% reduction in cooling capacity. Noteworthy, steady compressor power profile shown in Figure 6 is an indication of steady refrigerant mass flow rate.

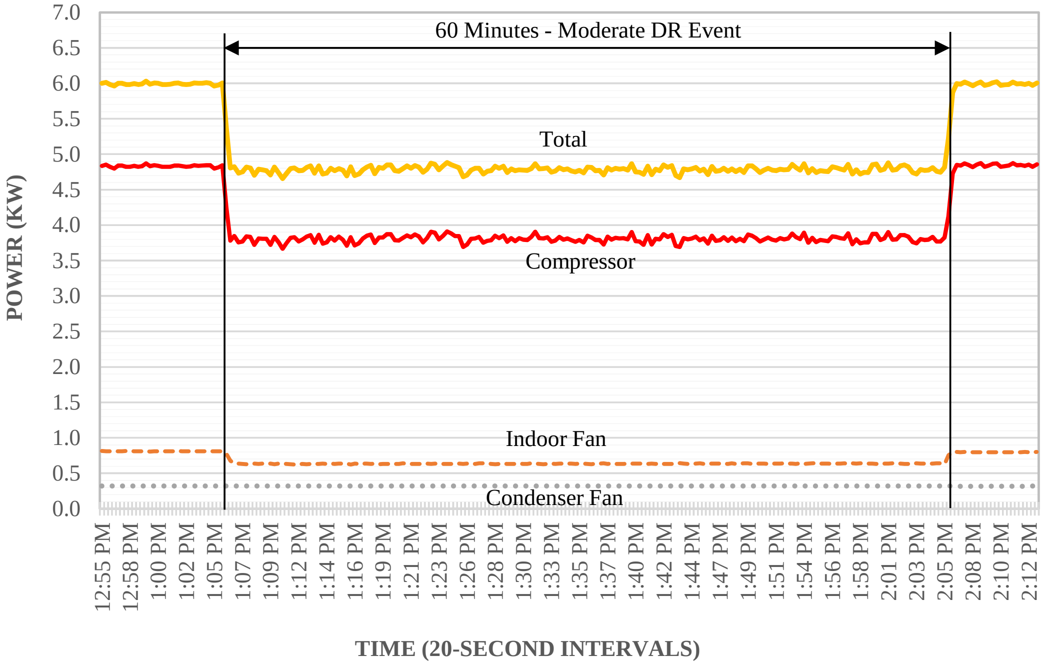


Figure 6: 20-Second-sampling power data profiles for moderate demand response event type [indoor DBT of 75°F and WBT of 63°F at outdoor DBT of 105°F]

Figure 7 illustrates the 20-second-sampling power data profiles before, during, and after a 60-minute high DR event for the indoor DBT of 75°F and WBT of 63°F, at an outdoor DBT of 105°F. Again, the illustrated power profiles are for indoor fan, condenser (or outdoor) fan, compressor, and total unit. Similar to previous test run (Figure 6), before and after the DR event, the unit was running at full speed or 60Hz with an average total power of 6.0 kW. However, once the DR event was initiated, the controller stopped the compressor operation for six minutes while the indoor fan continued operation at 20Hz, with an average power draw of 0.2 kW. Afterwards, the controller ran both the compressor and indoor fan at 40Hz for nine minutes. During this nine-minute period, the average total power was 3.9 kW. The controller cycled the compressor on and off while ramping up and down the indoor fan frequency for every 15-minute time intervals during the event, as intended. Combining on and off periods and averaging the total power during a 15-minute or 60-minute interval resulted in an average total power of 2.4 kW. This indicated that overall, the average total power was dropped from 6.0 kW to 2.4 kW – a 60% reduction in power.

Similarly, decreasing compressor speed resulted in a decline in the cooling capacity of the unit. Whereas the average cooling capacity during normal operation was 49,290 Btu/hr or 4.1 ton, during the DR event it was 42,664 Btu/hr or 3.6 ton. This was also a 13% reduction in cooling capacity. Although, to some extent, more reductions in cooling capacity for high DR event would be anticipated due to operating the compressor at lower speed levels compared to moderate DR event, this was not captured in the data. This fact could be attributed to slightly higher refrigerant mass flow rate at the beginning of the cooling cycles after unit being off for six minutes, which can be observed by spikes in compressor power demand profile in Figure 7, coupled with minor increase in refrigeration effect during those time periods. The fact that the refrigerant mass flow rate followed compressor power profile was expected.

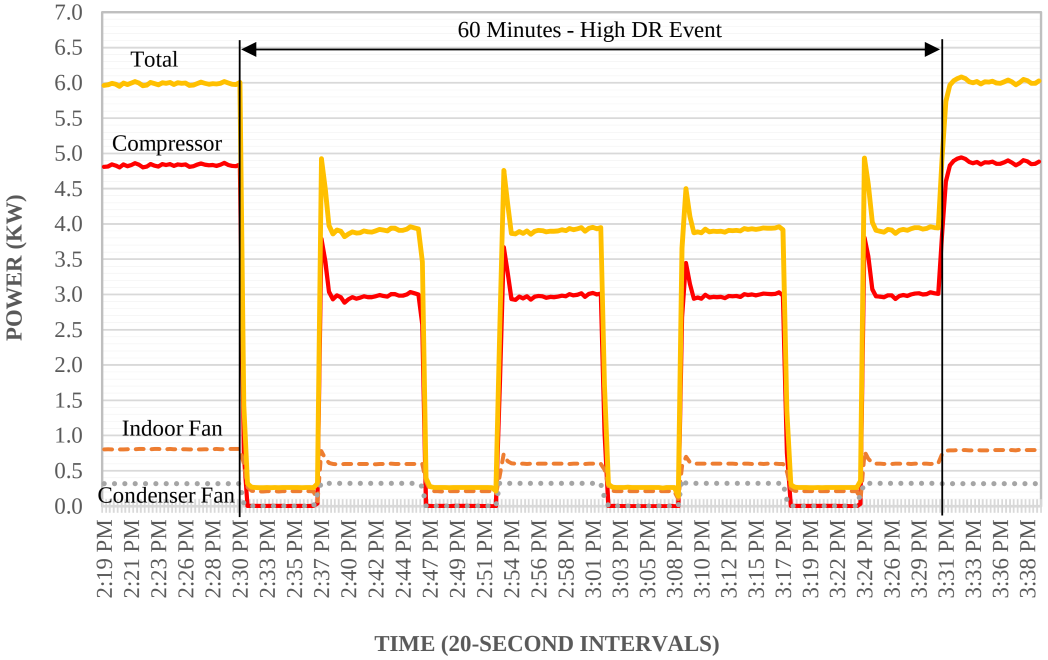


Figure 7: 20-Second-sampling power data profiles for high demand response event type
[indoor DBT of 75°F and WBT of 63°F at outdoor DBT of 105°F]

4.3 Representative indoor dry-bulb temperature variations

Figures 8 and 9 demonstrate variations in indoor DBT during DR events, for test runs with indoor DBT of 75°F and WBT of 63°F, at outdoor DBT of 105°F. Figure 8 is the 20-second-sampling indoor DBT profile for a moderate DR event, while Figure 9 is for a high DR event. In these figures, the total power profile is also included as a reference point. Again, due to controller's consistent response, the variation patterns observed in the indoor DBT for other test runs was same as those presented in Figures 8 and 9, according to the DR type.

For the moderate DR event scenario (Figure 8), the indoor DBT was 75°F prior to initiating the DR event. By the end of the event, it reached 82°F. This 7°F increase in DBT was due to running the unit at lower speed, causing a 13% reduction in the unit's cooling capacity. For the high DR event (Figure 9), the increase in indoor DBT was more significant. Prior to the DR event, the indoor DBT was 76°F, and it rose to 90°F by the end of the event. The reduction in cooling capacity along with on and off cycling patterns during the 60-minute high DR event caused the indoor DBT to increase by 14°F.

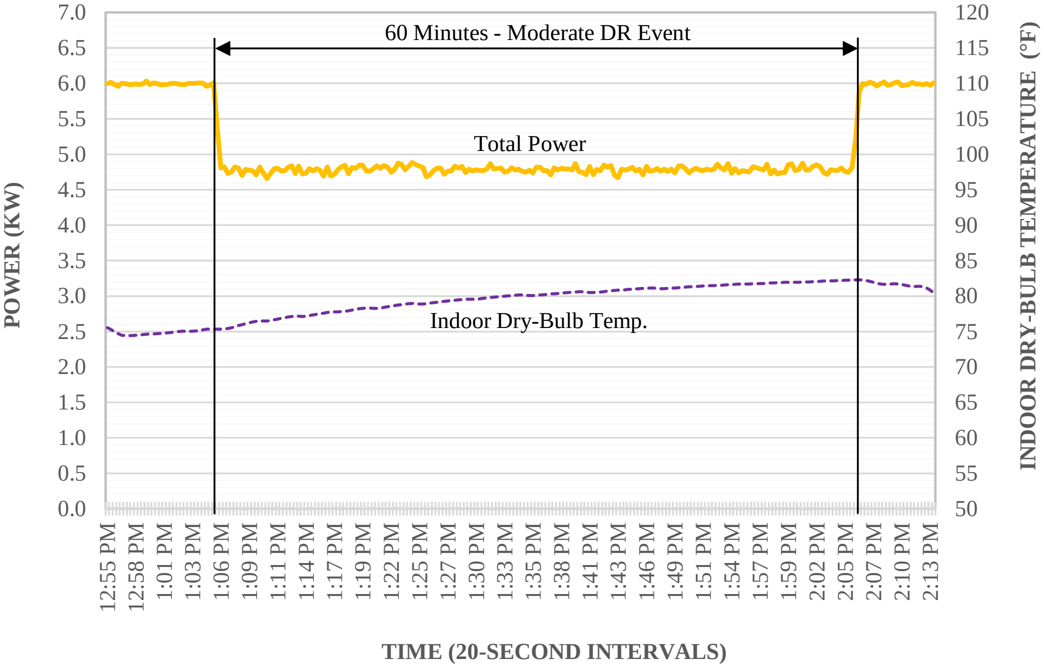


Figure 8: 20-Second-sampling indoor DBT and total power profile for moderate demand response event type [indoor DBT of 75°F and WBT of 63°F at outdoor DBT of 105°F]

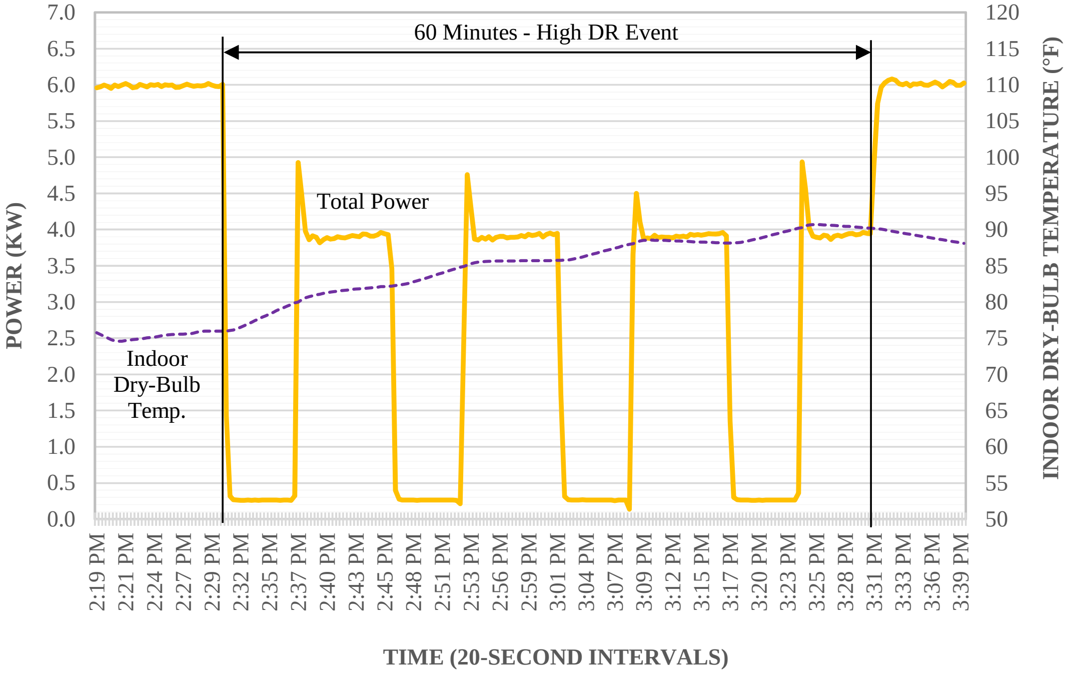


Figure 9: 20-Second-sampling indoor DBT and total power profile for high demand response event type [indoor DBT of 75°F and WBT of 63°F at outdoor DBT of 105°F]

4.4 Summary Data

Table 2 summarizes and compares the average total power values obtained during normal operations and during 60-minute DR events for all eight test scenarios. The comparison revealed that the most reduction in power demand was for high DR event scenarios where the controller cycled the unit on and off. For moderate DR event scenarios where the unit operated at reduced frequency (or speed levels) the power reductions were not as significant as they were for high DR scenarios.

Table 2: Summary of Average Total Power Data for All Test Scenarios

Test Conditions	DR Signal Type	Average Total Power During Normal Operation (kW)	Average Total Power During 60-minute DR Event (kW)	Percent Change or Average Power Reduction (%)
Indoor DBT of 75°F/WBT of 63°F, outdoor DBT of 95°F	Moderate	5.4	3.6	33
	High	5.5	2.2	60
Indoor DBT of 75°F/WBT of 63°F, outdoor DBT of 105°F	Moderate	6.0	4.8	20
	High	6.0	2.4	60
Indoor DBT of 80°F/WBT of 67°F, outdoor DBT of 95°F	Moderate	5.4	4.4	19
	High	5.4	2.2	59
Indoor DBT of 80°F/WBT of 67°F, outdoor DBT of 105°F	Moderate	6.0	4.7	22
	High	6.0	2.4	60

The impact of implementing DR strategies on the unit's cooling capacity are summarized in Table 3, listed in Btu/hr and cooling tonnage. The unit's cooling capacity degradation during normal operations and during DR events at an outdoor DBT of 105°F in comparison with 95°F is evident in Table 3. Combining the effects of elevated ambient DBT of 105°F with speed modulations, resulted in higher reductions in cooling capacities during DR events – it ranged between 12% and 14%. While for the outdoor DBT of 95°F tests, the reductions in cooling capacities during DR events stayed within 10% to 12%. The reduction in cooling capacity during high DR event was either same as or slightly lower than that for moderate DR event, which was not expected. This can be attributed to minor increase in refrigerant flow rate and refrigeration effect at the beginning of the cooling cycles during high DR events.

Table 3: Summary of Average Cooling Capacity Data for All Test Scenarios

Test Conditions	DR Signal Type	Average Cooling Capacity During Normal Operation Btu/hr [ton]	Average Cooling Capacity During 60-minute DR Event Btu/hr [ton]	Percent Change or Reduction in Average Cooling Capacity (%)
Indoor DBT of 75°F/WBT of 63°F, outdoor DBT of 95°F	Moderate	52,371 [4.4]	46,047 [3.8]	12%
	High	52,206 [4.4]	46,364 [3.9]	11%
Indoor DBT of 75°F/WBT of 63°F, outdoor DBT of 105°F	Moderate	48,756 [4.1]	42,246 [3.5]	13%
	High	49,290 [4.1]	42,664 [3.6]	13%
Indoor DBT of 80°F/WBT of 67°F, outdoor DBT of 95°F	Moderate	54,797 [4.6]	49,045 [4.1]	10%
	High	53,685 [4.5]	48,561 [4.0]	10%
Indoor DBT of 80°F/WBT of 67°F, outdoor DBT of 105°F	Moderate	52,289 [4.4]	44,942 [3.7]	14%
	High	51,311 [4.3]	45,205 [3.8]	12%

Table 4 lists the recorded indoor DBTs at the start and at end of DR events. It also shows the increase in indoor DBT due to DR events. As expected, the rise in indoor DBT was more noticeable for high DR event types due to the unit's frequent on and off cycling during the events. Since the unit operated continuously during the moderate DR event, however, the rise in indoor DBT was less than 10°F for these test runs.

Table 4: Summary of Indoor Dry-Bulb Temperature Data for All Test Scenarios

Test Conditions	DR Signal Type	Indoor DBT at the Start of DR Event (°F)	Indoor DBT at the End of DR Event (°F)	Increase in Indoor DBT (°F)
Indoor DBT of 75°F/WBT of 63°F, outdoor DBT of 95°F	Moderate	75	83	8
	High	76	92	16
Indoor DBT of 75°F/WBT of 63°F, outdoor DBT of 105°F	Moderate	75	82	7
	High	76	90	14
Indoor DBT of 80°F/WBT of 67°F, outdoor DBT of 95°F	Moderate	80	89	9
	High	81	98	17
Indoor DBT of 80°F/WBT of 67°F, outdoor DBT of 105°F	Moderate	80	86	6
	High	80	95	15

5. CONCLUSIONS AND RECOMMENDATIONS

This research study confirmed the controller's ability to respond to both moderate and high DR event notifications in a consistent manner. It also verified the pre-programmed strategies for each DR event type.

The DR potential and thermal comfort impacts are summarized as follows:

- The reduction in average total power is more significant for high DR events, and it can reach up to 60%.
- The reduction in average total power for moderate DR events can range between 19% and 33%.
- The rise in indoor DBT due to high DR events is more significant, and it can range between 14°F and 17°F.
- The rise in indoor DBT due to moderate DR events can range between 6°F and 9°F.

As the first series of investigations in DR for air conditioners, the results point out to the importance of strategies in controlling the unit's operation and the associated impact on thermal comfort levels. The outlined rise in indoor temperature makes a case for steering away from the traditional approach of sacrificing thermal comfort at peak outdoor ambient conditions to reduce demand spikes on the grid. Further, it calls for enhancements in controller technologies, to assess and limit human comfort impacts. Future studies should consider evaluating control devices with different strategies, under a 24-hour dynamic load profile. These studies should also consider the specifications of AHRI Test Standard 1380, once it is published.

Finally, it should be noted that the presented findings here are for a set of particular strategies programmed in the controller under certain climatic conditions. Results will vary for different strategies and climatic conditions.

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