Energy and Buildings 97 (2015) 47–55

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Round-trip efficiency of fast demand response in a large commercial air conditioner

I. Beil[a,*], I.A. Hiskens[a], S. Backhaus[b]

[a] Department of Electrical Engineering and Computer Science, University of Michigan, 1301 Beal Ave., Ann Arbor, MI 48109-2122, United States
[b] Materials Physics and Applications Division, Los Alamos National Laboratory, Los Alamos, NM 87545, United States

ARTICLE INFO

Article history:
Received 23 April 2014
Received in revised form 10 February 2015
Accepted 14 March 2015
Available online 2 April 2015

Keywords:
Demand response
Ancillary services
Energy efficiency
Heating ventilation and air conditioning

ABSTRACT

Air conditioning (AC) of large commercial buildings represents an attractive target for many different forms of demand response (DR) including DR for ancillary services (AS) such as frequency regulation. The operating cost of such DR is typically discussed in terms of occupant discomfort. However at fast timescales, perturbations to well-functioning building controls may increase the total energy consumption relative to a baseline that does not provide DR ancillary services (DR-AS). The extra energy is a cost of control to the asset owner and should be factored into the cost of providing DR-AS. We performed DR experiments on a ∼30,000 m^2 office building, and at the 15-min time scale of these experiments, we find the extra energy consumption to be significant. Similar to battery energy storage, we express the energy cost in terms of a round-trip efficiency and use this metric in a simple economic analysis of the cost of frequency regulation from these resources and discuss potential impacts on advanced load management methods.

1. Introduction

The penetration of renewable generation is increasing significantly in many electrical grids. In the U.S., much of this expansion is being driven by renewable portfolio standards (RPS) [1] that mandate a certain fraction of generation be derived from renewable resources, with wind and photovoltaic (PV) generation being the primary contributors. Both of these resources are variable and stochastic, i.e. they have limited controllability. As the penetration of renewable generation increases, there is less room in the generation stack for controllable generation for mitigating renewable fluctuations. Viewed in this way, even the expansion of flexible natural gas generation in many parts of the U.S. may ultimately be limited in its ability to provide these balancing resources. Other controllable resources will be required to provide such ancillary services (AS).

Grid-level energy storage is one candidate to provide these services. Pumped hydro storage is an economical, highly efficient form of energy storage, however, its availability is limited by local geography [2]. Some forms of battery energy storage can have roughly similar efficiency, however, the capital costs remains stubbornly high. The lack of universally available storage has encouraged the development of demand response (DR). The intent of DR load control is to adjust the time when energy is consumed to assist with the management of generation-load balance. DR is used in many electrical grids to provide demand response ancillary services (DR-AS) with the majority of these uses being spinning reserves [3], i.e. DR-AS that is called on relatively infrequently. The impact to the interrupted load is primarily disruption of the end use. Other forms of DR-AS, such as frequency regulation service [4], will require much more frequent and continual modification of load behavior which may have performance implications beyond just a disruption of the end use.

The assumption by many DR research efforts [4–7] is that disruption of the load by DR has little or no effect on the total energy consumption or that the effect is insignificant compared to the value of the DR service. For loads that are simply deferred, for example dish washing and clothes drying, or for grid services that only require a few load adjustments per day, this assumption is likely quite good. However, if DR-AS requires that load consumption be modulated about a mean level on sub-hourly timescales, this assumption may not hold and additional energy consumption may be required to serve the disturbed load. Some experimental [8] and simulation [9] work has demonstrated an increase in average total energy consumption due to the relatively slow preheating or precooling of homes driven by time variable energy pricing. However, insufficient attention has been given to possible

* Corresponding author. Tel.: +1 734 646 2606.
E-mail addresses: ianbeil@umich.edu (I. Beil), hiskens@umich.edu (I.A. Hiskens), backhaus@lanl.gov (S. Backhaus).

http://dx.doi.org/10.1016/j.enbuild.2015.03.028
0378-7788/

energy losses incurred because of DR control and especially DR-AS control.

Large commercial air conditioning (AC) systems are attractive loads for DR and DR-AS applications because they already include relatively sophisticated control and communications architectures, reducing the expected incremental capital cost of adding DR capability. In contrast, a population of small residential loads may provide a well-understood and repeatable demand profile [10], but the capital cost of the enabling control and communication infrastructure is significant. The operational or control cost of AC-based DR is typically discussed in terms of occupant discomfort – a very important metric because a DR control that exceeds comfort levels too often could be discontinued. Occupant discomfort depends upon the DR control system and how it weights discomfort versus other objectives, e.g. accuracy in tracking load power reference signals. However, there may exist additional operating costs. If the building controls for a large commercial AC system are operating in a quasi-steady state, perturbing these operations will likely increase the time-averaged energy consumption, thereby creating additional operating costs for the asset owner who is providing the DR-AS service. This manuscript focuses on characterizing these additional energy costs for one type of large commercial building AC at timescales comparable to those in frequency regulation service.

We have performed DR-AS experiments on a ~30,000 m^2 office building to develop a methodology for measuring the extra energy consumption, to determine this extra consumption for one class of commercial buildings using one type of AC system, and to develop an economic model for the variable operating cost of the DR-AS. The DR experiments are primarily carried out at the 15-min time scale, a speed appropriate for mitigating fluctuations due to wind and PV variations, and approaching the control speeds needed for participation in frequency regulation markets [11]. We characterize this AC-based DR in terms of a round-trip efficiency so that it can be directly compared to other forms of energy storage, e.g. the round-trip energy losses incurred when charging and discharging a battery.

The remainder of this manuscript is organized as follows. Section 2 presents a review of relevant DR literature. Section 3 provides a brief description of the AC system used for experimentation, sufficient for understanding the main results. Section 4 introduces an analogy to round-trip efficiency of battery charging/discharging that will be useful in the discussion of our experiments. Section 5 describes the experimental protocol used for determining AC-based DR round-trip efficiency – a method we believe is applicable to most large commercial AC systems and large aggregates of residential AC units. Section 6 presents the results of our measurements and a comparison with additional analysis of data from related experiments [8] and simulations [9]. Section 7 provides a discussion of our results in terms of an economic model for the DR service and some potential implications for advanced load control. Finally, Section 8 presents our conclusions and a discussion of potential future work.

2. Literature review

The physical structure of large commercial AC systems is interconnected such that control actions taken by one component affect the behavior of all attached components, often leading to complex dynamics. For control purposes, many researchers describe the behavior of these systems using reduced-order models, e.g. Ziegler-Nichols tuning [12] or self-learning neural networks [13]. Such approaches allow the operator to aggregate the many individual control points and devices in the system into a few key control setpoints. In previous work [14], we take a related approach that represents the state of a large number of similar devices (variable air volume units, described in Section 3) using a probability distribution, and relates this distribution to the AC fan power consumption. We also developed a model of the dynamics of this distribution and used this predictive model in an open-loop method capable of providing DR-AS at speeds approaching those required for participation in frequency regulation markets. We use this same open-loop control strategy [14] in the current work.

The work in this manuscript also builds on previous experimental work on DR in commercial AC systems. This includes [15] which demonstrated load shedding by AC systems across geographically separated commercial buildings when exposed to increases in a dynamic electrical price on hour-long timescales. In a separate test presented in [16], the results in [15] were validated on a larger population of buildings subject to critical peak electricity pricing. Experiments using customer AC loads to provide spinning reserve services [17] have also been conducted. The Open Automated Demand Response (OpenADR) communication protocol [18] has been used to control the AC load of buildings [19] by sending both price and load curtailment signals. However, this previous work is primarily focused on longer time scales and infrequently called DR services. Our focus in this manuscript is on faster and continuously controlled DR-AS such as frequency regulation.

Some recent work has focused on more advanced AC control paradigms including genetic algorithms [20], occupancy-based control of entire building floors [21], model predictive control (MPC) to reduce transient loads [22], and MPC in conjunction with weather forecasting to regulate an entire building AC system [23]. Predictive control schemes have also been used to minimize building energy costs under time-of-use pricing [9,24] as well as under dynamic pricing scenarios [9,25]. Larger system studies have investigated the impact of DR on entire electrical distribution circuits [26]. However, most of this work is focused on control at slow time scales rather than the fast frequency regulation we consider here. Several efforts used simulations [4,27] and experiments [27,28] to examine commercial AC response to frequency regulation signals on shorter-term timescales, but these studies did not include the loss mechanisms examined in our experiments.

3. AC system description

The details of commercial AC systems vary from building to building, with the larger systems often being custom designed to the particular application. However, many large systems share a common underlying structure. The AC system in this work (see Fig. 1) is comprised of a central chiller plant that distributes chilled water to the heat exchangers in several independent air handling units (AHU). The fans in the AHUs circulate building air through the heat exchangers and to the conditioned spaces. The flow of cold air into each space is regulated by individual variable air volume (VAV) units. The rest of this section provides details of the AC system that are important for understanding the properties of the DR-AS experiments. For a more in depth discussion of the HVAC layout, see our previous work [14].

For the purposes of this discussion, we begin at the VAVs which are the air inlets to the conditioned spaces (see Fig. 1). A damper valve in the VAV adjusts to regulate the amount of cooled air flowing from the supply air duct into a conditioned space. Unlike the discrete, hysteretic control of small AC units, the error signal from the conditioned-space thermostats is used by a local proportional-integral-derivative (PID) controller to continuously vary the VAV damper valve opening. The damper valves can be actuated between 100% (fully open) down to about 20–30% [29]. The lower limit is set to ensure the conditioned space always receives a required minimum level of ventilation. The local PID controller and the mechanical response time of the damper valve opening determine