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A new thermostat for real-time price demand response: Cost, comfort and energy impacts of discrete-time control without deadband

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HIGHLIGHTS

- A new thermostat design that enables reliable aggregate demand response for ancillary services.
- Performance metrics to rigorously design, monitor, and optimize the demand response performance.
- Demand response performance objectives utilities can use to deliver load-based ancillary services.
- A thermostat design that gives consumers control of the demand response services they provide.
- A numerical method to evaluate the aggregate impact changes to residential thermostat designs.

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ABSTRACT

Thermostatically controlled electrical loads can provide valuable energy storage and are prime candidates for fast acting demand response (DR) that can be used to mitigate highly variable renewable power generation and limited availability of ramping resources. When conventional thermostats are retrofitted for real-time price DR control, significant control errors can arise, particularly in the form of dispatch control drift. This paper identifies the underlying causes and presents a new residential thermostat design that enables accurate aggregate load control. The new design gives rise to linear time-invariant models of aggregate load control and demand response, which facilitate the design of highly accurate load-based regulation services for electricity interconnections. Detailed simulation and performance studies coupling a residential house and feeder models are presented to show how consumer comfort and cost savings are achieved and how energy use is impacted for cities in three different climatic zones. During peak times, the new thermostat imparts the entire residential load an energy demand elasticity of about 10–25%. Larger demand elasticities could be achieved by extending the control strategy to other residential thermostatic loads. The proposed thermostat design can operate in the real-time distribution capacity auction system and can provide all the benefits associated with transactive systems, and in particular facilitate increased integration of renewable resources.

1. Introduction

Demand response is increasingly regarded as an important resource for electricity interconnections in industrialized economies. Demand response provides both economic and technical benefits that far outweigh their costs [1]. The United States Federal Energy Regulatory Commission issued FERC Order 745 specifically to encourage participation and ensure the competitiveness of demand resources in organized wholesale markets [2]. In spite of the regulatory setback dealt by the US Court of Appeal's decision to vacate the order [3], both proponents and critics of FERC's approach agree that demand plays a crucial role in mitigating both the market power of electricity suppliers [4] and the intermittency of renewable generation resources [5] while maintaining the comfort and satisfaction of consumers [6].

Research into fast-acting demand response was originally motivated by technical pressures to improve system efficiency while retaining a high level of consumer satisfaction. Direct load control and time-of-use demand response strategies have been widely used for decades but often show limited benefits at subhourly levels [7]. To address these limitations market-based real-time

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demand response based on microeconomic theory [8] was initially demonstrated in computer resource allocation [9] and proposed for electricity operations [10]. Work on multi-commodity flow [11] and building thermal control [12] demonstrated the applicability of markets to optimal micro-allocation problems in energy. In all these approaches, markets are used to find short-term Pareto-optimal allocations of a constrained resource in a technical system by determining the short-term price at which the supply equals demand over the coming interval of time. Individual responsive system components are equipped with new control elements to bid for resource utilization to satisfy consumer needs and respond to changes in price by changing resource usage in the short term. The benefits of this approach have been shown to reach throughout electric interconnections including enhancing the penetration of intermittent renewable resources [13].

However, incentives, dispatch methods and compensation of demand response remain challenges that restrain system planners and operators from adopting these fast-acting control strategies. Hogan [14] argues that the "the ideal and economically efficient solution regarding demand response compensation is to implement retail real-time pricing at the LMP, thereby eliminating the need for [wholesale] demand response [compensation]." To investigate the technical questions regarding the large-scale feasibility of near real-time demand response the US Department of Energy funded the 2006 Olympic Peninsula [15] and 2013 Columbus Ohio [16] demonstration projects. Both projects sought to address the open technical questions regarding the so-called "price-to-devices" challenge [17] by demonstrating the *transactive control* approach on retrofitted control equipment that integrates small-scale residential, commercial and municipal electrical equipment with utility electric power distribution system operations as a first step toward integrating distributed generation and demand response into wholesale operations. "Transactive control" in this context refers to a distributed resource allocation strategy that engages both electricity suppliers and consumers using market-based mechanisms extending down to the retail level for the purpose of enabling demand response by the utilities at the wholesale level [18].

This paper addresses potentially significant shortcomings of the existing conventional thermostat control retrofits uncovered by the demonstration projects. Specifically, under certain circumstances the demand response quantity dispatched by the retail markets using the real-time price was not sustained for the entire duration of the market clearing interval. In addition, any significant sustained deviation in the price could lead to unpredictable demand response deviations because of changes in the diversity of thermostatic device states. These problems lead to increased uncertainty about the reliability demand response services based on conventional thermostats and lack of confidence in the effectiveness of demand response control systems. These shortcomings are mitigated by a fundamental redesign of residential thermostats when used for fast-acting demand response. In particular the new thermostat eliminates the use a deadband altogether and imposes a discrete-time control model instead. These steps seem to individually violate conventional wisdom about how thermostat should work, i.e., (1) deadbands are necessary to avoid fast cycling of heating/cooling equipment and (2) discrete-time control results in excessive overshoot and degrades consumer comfort. However taken together they represent a novel solution to the problem of obtaining accurate large-scale fast-acting demand response from residential energy systems. After reviewing the background of the transactive control problem, this paper reports the preliminary results of those investigations.

Without mechanisms like transactive control, price-responsive load requires directly engaging a very large number of very small participants in the unit-commitment and economic dispatch process [19]. The computational complexity of the centralized optimal dispatch problem makes this impractical for anything more than the thousands of larger suppliers already involved [20]. Strategies extant for addressing this challenge generally involve retail demand aggregation that enables the integration of demand units by proxy of a reduced number of larger representative units. Private entities such as Enernoc have based their business models on this approach. These are used primarily on commercial buildings where the control systems are more amenable to this integration and the number of control points per Watt of resource is lower than it is for residential buildings. Unfortunately, this leaves nearly half the available building load untapped as a demand resource for utilities.

Previous demand response through heating/cooling system control has generally focused on retrofits to existing thermostats. Rather than fundamentally rethinking the operation of thermostats, these retrofit strategies added new capabilities to thermostats to enable demand response behavior needed by utilities for peak load reduction or shifting. Most of these methods are focused on direct load control design either for peak load reduction [21,22] or for regulation services [23,24]. Indirect load control methods are typically extensions of direct load control methods that include additional control component to convert incentive signals such as prices to comfort signals such as thermostat offsets [15,16].

Using markets to solve electricity resource allocation problems at the wholesale bulk system level is well-understood [25]. But transactive control takes the idea to the retail level by solving the resource allocation problem at the distribution level first before integrating it at the wholesale level. These retail markets are designed to find an allocation of distribution capacity, distributed generation and demand response to resolve how much wholesale energy resource is required and determine how much distributed generators should produce and customers can consume in the coming time interval. Transactive control systems use sub-hourly distribution capacity markets to determine energy prices that minimizes the imbalance between supply and demand for electricity for participating equipment during the next operating interval [26]. These systems compute 5-min retail real-time prices (RTP) for energy that reflect the underlying wholesale LMP plus all other distribution costs and scarcity rents arising from distribution constraints. In cases where large amounts of renewable resources are available the real-time price can be less than the LMP. Negative prices are even possible when a surplus of must-run generation is available. The RTP comes under a new tariff presumably designed to be revenue neutral *in the absence* of demand response.

Distributed generation, load shifting, demand curtailment, and load recovery can all be induced by variations in real-time prices. Given these responses transactive control systems can reduce the utility's long-term exposure to price volatility in the wholesale market and the costs of congestion on the distribution system [27]. These can reduce the long-term average cost of energy for consumers who are willing to forgo consumption in the very short-term. Short-term retail prices are discovered using a feeder capacity double auction and these prices can help manage distribution, transmission or bulk generation level constraints. Distributed generation and demand response are dispatched based on consumers' preferences, which they enter into an advanced thermostat that acts on their behalf as an automated agent bidding for electricity. Transactive thermostats both bid for the electricity and modulate consumption in response to the market clearing price. By integrating this response to a price signal that reflects anticipated scarcity, the system closes the loop on energy delivery and improves resource allocation efficiency by ensuring that consumers who value the power most are served prior to those who