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An algorithm for optimal management of aggregated HVAC power demand using smart thermostats

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HIGHLIGHTS

- An algorithm for optimal management of aggregated HVAC power is presented.
- The HVAC control problem is formulated as a jobs scheduling problem.
- The algorithm is analytically proven to be optimal.
- Simulation results show an improvement in HVAC demand reduction by 130% over a traditional approach.
- Demand restrike is limited to pre-DR-event level.

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ABSTRACT

This paper presents an algorithm for optimal management of aggregated power demand of a group of heating, ventilating and air-conditioning (HVAC) units. The algorithm provides an advanced direct load control mechanism for HVACs that leverages the availability of smart thermostats, which are remotely programmable and controllable. The paper provides a theoretical basis and an optimal solution to the problem of cycling a large number of HVAC units while respecting customer-chosen temperature limits for the purpose of maximum load reduction. The problem is presented in a new light by transforming it into a job scheduling problem and is solved using a combination of a novel greedy algorithm and a binary search algorithm. By leveraging widespread availability of smart internet-based (also referred to as IoT-based) thermostats in today's environment, the proposed approach can be readily applied to residential buildings without additional electrical/IT infrastructure changes.

1. Introduction

Demand side management is an alternative to achieving energy balance in the electric grid by means of altering electrical demands to suit available supply. Historically, demand side management has been used for long term energy balance through energy efficient appliances, financial incentives, consumer education and government regulation [1]. It has evolved to incorporate load profile management through energy audits, direct load control and subsequently real time pricing [2]. Demand response (DR) is one method of demand side management where end-use electricity consumption changes in response to changes in electricity price or to alleviate system stress condition [3]. Surveys on various DR methods are available in [4–6] and real-world applications can be found in [7]. One of the most popular DR methods for managing aggregated power of a group of customers is direct load control (DLC) [8] in the residential sector [9], where a utility remotely turns off electrical equipment at customer premises, e.g., HVACs, during the time of system stress, disregarding customer comfort.

In the literature on smart DLC for HVAC, HVACs are crudely divided into groups based on their comfort requirements and building thermal characteristics, then an empirical fuzzy rule [10] or a predictive control method [11] is applied to control the duty-cycle for each group. These methods employed, however, neither explicitly take care of customer temperature preference nor achieve optimal load reduction. Authors in [12] use peculiar chilled water thermal storage capacity to offer DLC in commercial buildings, which cannot be generalized for the residential settings. In [13] adaptive control based DLC is explored where a power reduction requirement is converted to set-point change requirement to feed into a classical thermostat based controller. The study shows a simulation result where the power has been successfully limited to 90% of the original peak but whether that is the maximum reduction attainable is unknown. Similarly arbitrary change of temperature set-

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points are shown to achieve some arbitrary reduction of power consumption during a critical period in [14]. In [15] double auction based transactive control is used to set-up a capacity market to limit the aggregated HVAC power. However, the power limit imposed is arbitrarily chosen and the transactive control used may not be optimal to control the population of HVACs. In [16] dynamic price based transactive control is studied for its efficacy in reducing the peak. But the price signal used is arbitrarily chosen and the reduction attained is far from optimal. Our previous work on transactive control [17] shows that a simple price signal based transactive control can reduce load during a high price period but creates a restrike after the event.

There are also a substantial number of research work on optimal DR, focusing on task scheduling problems. Authors in [17–19] solve an optimization problem to calculate the optimal schedule for each appliance that incurs minimum cost. This method only addresses scenarios where buildings are concerned about their cost minimization but the presence of other households trying to do the same thing has no effect on the solution. Authors in [20] indirectly address this problem by setting the upstream price as a function of the aggregated power, but it is still based on a primitive task-scheduling problem and as such does not take into account the fine thermal dynamics of HVACs. Similarly, authors in [21–23] address aggregated appliance control through optimal scheduling, but peculiar HVAC dynamics is ignored. In our previous work [24], DR at a single house is achieved by scheduling loads according to their priority and comfort requirement but the application of the algorithm for aggregated cases remains unexplored. In [25], HVAC thermal dynamics are incorporated but individual comfort constraints and the aggregated dynamics are ignored. In [26], HVAC thermal dynamics is taken into account and optimization for cost reduction based on dynamic price is performed but aggregated dynamics is disregarded.

There are also research work that specially targets aggregated control of HVAC or thermostatically controlled loads (TCL). In [27], a probabilistic aggregate model of a collective HVAC system is used for demand response but the aggregate power frequently exceeds the reference and also temperatures of some buildings exceed customer preference limits. In [27–29], an aggregated model is developed for HVACs and their potential for load following is explored. HVACs are controlled based on priority established by calculating temperature distance from the boundary. Authors in [30] develop a similar approach for water heater control. Although the control methods used in these papers are intuitive their optimality is not proven. The research work in [31] converts HVACs into generic second order continuous time TCLs and creates an aggregated battery model to study the collective behavior on average; but the aggregate model cannot take into account instantaneous co-incidence event of different HVACs. In [32], an iterative demand bidding is used to arrive at an optimal schedule of customers so that their collective utility is maximized–but there is no direct control on the amount of power reduction and might take long time for the iterative bidding to stabilize and deliver HVAC control schedules.

In more recent works, an aggregated model of AC has been developed and an optimal DR based on dynamic programming that respects comfort constraints has been proposed in [33]. Similarly, aggregated control of residential HVAC for peak load shaving has been explored in [34] and optimal DR using MPC approach can be found in [35–37]. In [38], authors present mechanism for optimal scheduling of smart appliances in the context of a smart community for the purpose of peak load reduction. Transactive control based DR is explored in [39]. A generic modelling technique also applicable to HVAC for fast-acting DR can be found in [40]. However, all of these research is concerned with optimal DR in presence of an upstream price signal or by creating various pricing scheme, which is not applicable to the problem we are exploring. In [41], aggregated control of HVAC for frequency regulation using a sliding-window based control is explored while their control for load balancing service is explored in [42].

In the area of DLC for HVACs for peak shaving, recent work close to ours can be found in [43]. While authors in [43] minimize user comfort violations by doing a fair allocation of the comfort violations to reduce the peak load by an arbitrarily set amount, this work aims at meeting the user comfort requirement (that the user agreed to in the contract), and achieving maximum attainable load reduction. Hence the novelty and contribution of this work is to find the maximum possible load reduction, and show a method to optimally achieve it, backed by an analytical proof.

We propose a novel control algorithm for a population of HVAC units that uses a combination of a novel greedy algorithm and a binary search algorithm to keep the aggregated demand (kW) at the lowest possible level during a control duration. The proposed approach explicitly considers comfort constraints (in terms of upper and lower temperature limits) of individual customers by maintaining indoor temperatures within their preference bounds. Although there is abundant research that considers HVAC thermal dynamics, user comfort constraints and aggregation effects for HVAC control, as per our knowledge, this approach in the context of finding the maximum load reduction potential given a DR period is new. The proposed greedy algorithm for HVAC control is simple, intuitive and highly efficient. This paper specifically analyzes HVAC control dynamics, presents an intuitive problem formulation for optimal load control, and analytically proves the solution optimality. This contributes to theoretical clarity on the problem of aggregated HVAC control. Although the work presented here can be easily generalized to any TCL, this paper focuses on HVAC control as it is the most popular one in today's environment, and there is a widespread adoption of smart WiFi thermostats. No such smart thermostats are widely available for controlling other TCLs like water heaters or refrigerators. This means large scale implementation of the proposed algorithm for HVAC control is possible without any additional infrastructure and without the installation of A/C cycling switch that is being done today for HVAC DLC. Although applicable for both heating and cooling, for brevity, the rest of the paper focuses on the cooling mode of operation.

The contributions of the paper can be summarized as following:

(1) The paper presents a novel linear-time algorithm to find the maximum load reduction potential for an aggregation of houses such that their comfort requirements are not violated.
(2) Associated algorithm to optimally control the HVACs in those houses such that the aggregated power is kept at the minimum value while respecting the comfort requirement is also presented.
(3) The problem of controlling the HVACs is transformed into an intuitive form of Job scheduling problem which provides theoretical clarity to the problem.
(4) The optimality of the algorithm is analytically proven.
(5) Optimal control of HVAC in response to DR signals presents a novel and important work in the field of intelligent building energy management system.

2. Framework and problem formulation

Let us consider an aggregation of N residential customers who have signed up with a DR aggregator, like EnerNoc, which can perform collective control of these customers to provide load reduction DR service to the utility or to bid this demand reduction potential into a capacity market [44]. It should not be hard to find willing participants for the proposed program since there are already customers who are participating in traditional HVAC DLC programs where they agree to let the utility remotely turn off their HVAC for a fixed duration of time (without regards for the indoor temperature) in exchange for some rebates. At minimum those customers should be willing to participate in the proposed form of DR which ensures that the temperature will be kept within a pre-agreed comfort bounds. The overall framework is shown in Fig. 1, where there is one aggregator and N houses, each with an IoT-based thermostat. There is also a controller dedicated for each