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A self-learning algorithm for coordinated control of rooftop units in small- and medium-sized commercial buildings

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HIGHLIGHTS

- Proposed an indoor temperature prediction algorithm using coarse-grained thermostat data.
- Designed a software solution for RTU coordinated control during a DR event.
- Tested algorithm in a real-world office building, showing effective peak load reduction.

ARTICLE INFO

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RTU coordination
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ABSTRACT

With the advent of the smart grid, demand response (DR) has been implemented in many electric utility control areas to reduce peak demand in buildings during grid stress conditions. However, small- and medium-sized commercial buildings typically do not deploy a building energy management (BEM) system due to high costs of commercially available solutions. Thus, their participation in DR events implies manual control and shutting down major building loads (e.g., air conditioning systems) without considering occupant comfort. With rapid development of Internet of Things (IoT) technologies, some cost-effective IoT-based BEM systems have become available. Based on such systems, this paper presents an algorithm to automatically coordinate the operation of rooftop units (RTUs) in small- and medium-sized commercial buildings, thereby meeting the specified power limit (kW) during a DR event while taking into account occupant comfort. The proposed algorithm has been designed to intelligently learn building thermal properties using coarse-grained indoor temperature data from thermostats, thus avoiding the deployment of sophisticated sensors network. A mixed-integer linear programming model has been utilized to determine an optimal RTU control strategy during a DR event. The peak load shedding performance of the proposed strategy has been tested in an office building in Blacksburg, VA, USA. The experimental result demonstrates that the building could achieve the required peak load reduction and the computation time required by the proposed algorithm is less than 5 min. This implies that with the proposed algorithm a building is capable of responding to a DR signal with a short notice, providing valuable demand-side resources for electricity capacity and ancillary markets.

1. Introduction

Buildings use around 40% of the total energy consumption worldwide [1] and consume over 70% of the total electricity usage in the U.S. [2]. As the major consumer of electricity, buildings have potential to provide energy savings and relieve stress on electric power grids during peak hours. Many studies have been conducted in recent years on this topic. Authors in [3,4] propose a multi-agent control platform that learns from occupant feedbacks to increase building energy efficiency while guaranteeing indoor comfort. A similar system is proposed in [5] using fuzzy control and a multi-objective genetic algorithm. Authors in [6] introduces a BEM system based on two-stage optimization capable of optimal scheduling of building appliances. A peak load reduction system based on model predictive control and real-time pricing is presented in [7]. Among various appliances in the buildings, HVAC systems usually consume over 30% of the total building electricity usage [8] and their reactive power usage is directly related to power grid voltage stability. Therefore, HVAC systems are the major loads in buildings to be controlled. Research in [9] quantifies energy savings based on different HVAC set points. A centralized heating system control approach to make building demand responsive is studied in [10]. Authors in [11] demonstrate peak cooling demand shifting with the

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help of building photovoltaic and thermal storage systems. Instead of using global set point adjustment, a computing tool is proposed in [12] to optimally control set points of each thermal zone during a peak-load reduction event. Authors in [13] propose a fast chiller control strategy to enable buildings to participate in electricity ancillary services [14] and providing a spinning reserve to the smart grid [15]. Another work targeting large commercial HVAC control for participating in fast demand response is presented in [16].

Not only in academia, electric utilities and third party demand aggregators show tremendous interest in the involvement of buildings in grid load balance. Many demand response (DR) programs have been introduced to encourage peak load reduction in buildings during critical times [17–20]. These incentive-based DR programs usually require a customer to sign a contract to maintain the building's power demand below a certain kilowatt (kW) limit during a DR event in exchange of financial benefits. However, by studying the non-domestic sector of the short term operating reserve (STOR) market in the U.K., authors in [21] point out that the challenges for involving more end users to participate in demand reduction are: (1) the short response time (as short as 5–10 min) to generate an effective response scheme and (2) the concern for compromising occupants' comfort. Because of these unresolved challenges, authors in [21] reveal that only a small portion of end users are willing to participate in the load reduction DR program. This implies that for a building to actively participate in a DR event, a control system that can response quickly and automatically and considering occupant comfort is required.

While large modern commercial buildings equipped with sophisticated building energy management (BEM) systems usually are able to achieve an automatic control, smaller buildings (less than 50,000 square feet), which constitute majority of buildings (i.e., more than 90% of commercial buildings in the U.S.), mostly do not have such automation systems [22]. The main reason is the prohibitive price for designing, programing and deploying an automatic energy management system. According to [23], a basic BEM is costly with an average price of $2.50 (U.S. Dollar) per square foot and this number can be as high as $7, not to mention a hefty annual maintenance expenditure of about 10–15% of the initial cost. The high cost of a traditional BEM system means return on investment is a challenge for all, but large buildings. To solve this problem, with fast development in the area of Internet of Things (IoT), many IoT-based BEMs enabled by IoT-based smart devices are emerging as cost-effective solutions to those building owners. Capable of providing controllability, system awareness and intelligent controls (see Fig. 1), they are gaining popularity for their low-cost, flexibility and scalability features among small- and medium-sized buildings. An example of such an IoT-based solution is the U.S. Department of Energy-sponsored Building Energy Management Open Source Software (BEMOSS) [24–26].

However, as of today, most of the IoT-based BEMs are focusing on controllability and monitoring, the intelligent applications are not well-developed, such as DR implementation. To implement DR, power consumption in buildings can be reduced by turning off unnecessary lightings and plug loads, but the control of HVAC systems is not straightforward and might need some decision making assistance. Since most small- and medium-sized buildings use rooftop units (RTUs), the coordination of multiple RTUs can be an effective approach for load reduction in such buildings.

Nevertheless, reducing HVAC power consumption in a building during critical periods, usually hot summer days, will inevitably impact occupants' thermal comfort. Thus, a good indoor temperature prediction will facilitate the HVAC control to minimize any occupants' thermal discomfort in a building. Time series and neural network methods are widely used in such predictions [27–33]. Authors in [27] predicts the thermal behavior of an open office using both linear parametric and neural network-based nonlinear autoregressive models. A similar study using an autoregressive model is discussed in [28]. Authors in [30] compare the performance of four different models to predict building thermal behaviors. However, existing work depends heavily on sensor inputs, which causes extra investment for building owners to establish the sensor network. For example, CO2 and occupancy sensors are needed to measure the building occupancy level, while door/window sensors are needed to examine the open/close status of windows and doors. To tackle this issue, authors in [31–33] propose approaches for multiple RTU coordination using minimal number of hardware. Authors in [33] specify a fixed number of RTUs that are allowed to operate at the same time. However, by limiting the number of operating RTUs, a building might not be able to fully utilize the allowable demand (kW) limit in case the rated power of various RTU is different from each other. Instead, a power limit should be used to cap the total RTU power demand to allow greater building operation efficiency and minimize occupant discomfort. Other studies in the literature use simulation data or sophisticated sensor data for indoor temperature prediction model training, which is not applicable with emerging IoT-based BEM systems. The reason lies in that the indoor temperature measurement comes from smart thermostats due to the absence of a sophisticated sensors network in IoT-based BEM systems, and the measurement granularity of many commercially available smart thermostats is large. (For example, RadioThermostat: 0.5 °F, Honeywell: 1 °F and ICM thermostat: 1 °F.) Thus, with such coarse-grained data, thermal properties that most time-series approaches trying to capture are lost, and new approach adaptive to these data is needed.

In all, the literature review shows that in the electric industry, involving more buildings in peak load reduction is highly beneficial, needed but not well-accomplished. Even though IoT-based BEMs provide an affordable solution for small- and medium-sized buildings, an intelligent DR implementation based on this platform is yet to come. Therefore, the originality of this work is the self-learning algorithm for coordinated control of multiple RTUs that can be used with the

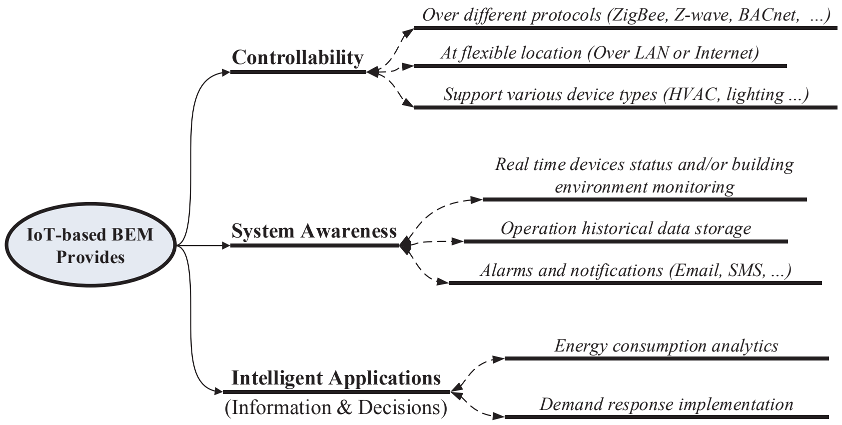

Fig. 1. Utilities of the IoT-based BEM.