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Implementation of demand response strategies in a multi-purpose commercial building using a whole-building simulation model approach

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ABSTRACT

This paper exploits a whole-building energy simulation approach to develop and evaluate demand response strategies for commercial buildings. The research is motivated by the increasing penetration of renewable energy sources such as wind and solar, which owing to their stochastic nature, means that enhanced integration of demand response measures in buildings is becoming more challenging and complex. Using EnergyPlus, a simulation model of a multi-purpose commercial building was developed and calibrated. Demand response strategies are evaluated for a number of building zones, which utilise different heating, cooling and ventilation equipment. The results show that for events of varying demand response durations, different strategies should be selected for each zone based on their thermal and usage profiles. Overall, a maximum reduction of 14.7% in electrical power demand was recorded when targeting a centralised chiller load, with smaller reductions for other decentralised building loads.

1. Introduction

Renewable energy sources (RES) integration in the electricity grid can be enhanced by demand response (DR) programs, in which participants change their electricity usage in response to RES availability or electricity prices [1]. Ireland, for example, is committed to increasing the level of renewable electricity production to 40% by 2020 [2]. In order to achieve this goal, significant work to manage the integration of increasing levels of instantaneous renewable penetration on the island is required [3]. RES power generation, especially solar and wind, largely depends on the time evolution of weather patterns, which are to varying degrees unpredictable, thereby causing potential imbalances between the power supply and demand on the gird [4]. As a way to compensate these imbalances, DR is utilised to provide the necessary flexibility to the grid. Moreover, DR can help to reduce electricity generation from fossil fuels by adjusting the demand to the present availability of fluctuating resources, when and where it is available, so curtailments can be reduced and the overall RES share can be increased [5,6]. Hence, DR events are increasingly likely to occur at times that were not traditionally considered as DR periods and as a result, requirements for electric load reduction from participants can vary significantly.

Among the different demand end use categories, buildings can potentially play a significant role in helping maintain the power supply and demand balance, since they account for almost 50% of the final electricity consumption [7]. Commercial buildings in particular, are capable of providing considerable load reduction and offer a range of options for demand management; thus they are of particular interest for DR implementation [8]. Heating, Ventilation and Air-Conditioning (HVAC) systems are their largest energy end-use category [9], which can also be controlled in order to utilise the building inherent energy storage characteristics and provide demand reduction [10].

As DR is utilised in building as a possible measure to enhance RES penetration, adaptive DR strategies have the capability to provide additional flexibility to meet utility/aggregator requirements. Such expectations are circumscribed by the need to know the magnitude of the load that should be shifted or curtailed, the time at which the response should be activated and the response duration. These three constraints constitute important utility/aggregator requirements. To address this challenge, control strategies capable of responding and adjusting building electricity demand profile is necessary to make the DR concept viable, especially in this changing operational environment. Such control strategies should be capable

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of controlling shiftable building loads dynamically and deploying these strategies as required without noticeably impacting user comfort.

The current paper focuses on the implementation of DR measures in commercial buildings in order to enhance RES penetration. Research efforts to date have mainly focused on the implementation of pre-defined DR measures for specific DR periods. However, DR events driven by RES availability exhibit unpredictability and therefore utility/aggregator requirements can vary significantly. This increases the complexity over existing DR approaches, as building responses should be triggered by utility/aggregator requirements, as well as factors such as weather conditions and occupancy. In order that buildings are capable of adapting to this changed operating environment, an evaluation of the different DR measures that can be implemented in a case of a DR event is required. The overall aim of the current research is to assess the DR potential of different HVAC components in a building and evaluate the impact of the developed DR strategies on occupant comfort. The main contribution of this paper is the combined evaluation of the potential of various DR strategies to shift/curtail building electric power demand under different utility/aggregator requirements, constrained by occupant comfort. In addition, strategies are evaluated at a zone level, thereby highlighting the significance of the zone thermal and usage profiles to the DR potential.

The paper is organized as follows: Section 2 provides an overview of related work. Section 3 outlines the adopted methodology. Section 4 describes the building and the developed simulation model. Building load analysis is given in Section 5. Section 6 outlines the assessment of the DR strategies and the final section concludes the paper.

2. Background

DR strategies are actions taken to change the scheduled operation of a system/load in order to reduce or increase the total energy consumption in the case of an event. Amongst the most common DR strategies that have been implemented to date are global temperature setpoint adjustment of building zones, which can be combined with space pre-conditioning, light dimming and temporary adjustment of different HVAC components. HVAC-based DR strategies are considered an excellent DR load resource, since they can constitute more than one third of the total building electrical power demand and are usually controlled by a BEMS [11].

One approach, the global temperature adjustment strategy, is based on the modification of the building cooling/heating setpoints for the different zones during the DR event [12]. Yang et al. [13] highlight that raising the cooling setpoint temperature can be applied to both new and existing buildings and provides a significant energy saving potential. Roussac et al. [14] applied two approaches in 33 mechanically ventilated office buildings in Australia. A static control strategy where the temperature setpoints were increased by 1 °C above normal for summer conditions and a dynamic approach where the setpoints were adjusted in direct response to variations in ambient conditions during building operational hours. Results indicate a 6% reduction in daily HVAC energy use for the static control strategy, which is slightly less than the 6.3% reduction reported for the dynamic approach. An adaptive comfort temperature model was developed by Mui et al. [15] for office buildings in Hong Kong, where the indoor comfort air temperature setpoints were tracked based on outdoor temperature, achieving a 7% of total energy saving. Sehar et al. [16] proposed an optimal control of building cooling air temperature setpoints which modifies the setpoints on a zone-by-zone basis based on occupant conditions in each zone during a DR event. A maximum peak load saving of 13.8% was achieved when implementing the control during a 4-h DR event in all the building zones for a summer weekday in Virginia.

Space pre-conditioning strategies target to shift the load from peak to off-peak demand hours. Xue and Shengwei [10] investigated the energy storage characteristics of commercial building thermal mass, by developing an interactive load management strategy of the HVAC systems. A noticeable load shift of 7.67% from office to non-office hours was recorded. Xu [17] investigated the capabilities of different pre-cooling periods and temperature setpoints in two large commercial buildings. HVAC electricity consumption was reduced by up to 25% over a 4-h shed period. Zone pre-heating and interruption of air-conditioning systems in an institutional building in Valencia for 1 or 2 h was investigated in [18]. Pre-heating during unoccupied hours was found to be capable of reducing the morning peak by 30%.

Motegi et al. [12] investigated two different DR strategies targeting directly the fan load in two commercial buildings in California for hourly DR events for a winter day. Initially, 50% of the fans encountered in the first facility were turned off achieving a maximum of 28% load reduction. A fan variable frequency drive (VFD) limit strategy was implemented in the second facility. During normal operation most fans were operated at 100% VFD, whereas during the DR event, the VFD was lowered to 60%, resulting in a 35% reduction on fan power compared to the baseline operation. Hao et al. [19] provided ancillary services to the power grid by manipulating the supply fan speed of air handing units (AHUs) in an institutional building in Florida based on time-varying regulation signal. Results indicate that during an hourly event, a reduction in fan electrical power demand of up to 15% was recorded without a noticeable impact in the building environment.

Chillers constitute a considerable load source that can be utilised in the case of a DR event. Xue et al. [20] proposed a DR control strategy targeting chiller loads by limiting chiller water flow rate and/or resetting the space temperature setpoints. HVAC system power demand reductions for a summer day ranged from 32 to 66.5% compared with the normal operation without significant impact on thermal comfort. Cui et al. [21] investigated active and passive cold storage capabilities of a commercial building in Hong Kong. Regarding the passive cold storage, it was observed that when a proportion of operating chillers were shut down for a 2-h period for a summer weekday, it resulted in a 34.5% reduction of the original chiller power consumption. Son et al. [22] proposed a method of day-ahead scheduling and rescheduling on the operation day, for a commercial building with chiller and energy storage system, considering the time-of-use tariffs in Korea.

Building energy simulation models have been widely used for performance analysis, as well as for examination of compliance with codes and standards [23]. Nevertheless, the use of building energy simulation models can be extended to other tasks including optimisation of design solutions during the building design stage or support building control systems during the building operational phase [24]. Moreover, detailed physics-based models have been widely used to demonstrate measures for reducing peak loads due to their ability to simulate complex system behaviour and alternative demand response control strategies [25]. Ma et al. [26], for example, proposed a model predictive control technique to reduce energy consumption and operating costs of building HVAC systems under a time-of-use tariff scheme. Additionally, Yoon et al. [27] developed a dynamic DR strategy, based on an EnergyPlus model, which changes the setpoint temperature to control HVAC loads depending on electricity retail price. For this reason, through the calibration process, significant discrepancies between simulated and measured building data should be eliminated to add value to and ensure reliability of the building energy models and extend their usage [28]. Broadly, calibration techniques can classified as manual or automated, either of which can include the use of