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Optimal and near-optimal indoor temperature and humidity controls for direct load control and proactive building demand response towards smart grids

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ABSTRACT

Shutting down part of operating chillers directly in central air-conditioning systems of buildings to meet the urgent demand reduction needs of power grids has received increasing attention recently. However, due to limited cooling supply during above demand response (DR) events, the indoor air temperature and particularly relative humidity would often increase to unacceptable levels, resulting in the failures of DR controls. Considering the restriction on power use during DR events, rational use of limited cooling supply turns out to be the inevitable choice. The feedback control strategies commonly-used today cannot properly deal with the environment and system control issues under limited cooling supply during DR events. However, no study on this problem can be found in the research literature. As the first effort, two control strategies (i.e., optimal and near-optimal) are developed to address the environment control issues (concerning both indoor temperature and humidity controls) under a pre-determined power limiting threshold during DR events. The optimal control strategy optimizes the air flow set-points of individual AHUs (air handling units) using model-based prediction and genetic algorithm to achieve the best possible indoor environment control. The near-optimal control strategy approaches such best environment control using a simple empirical method. Case studies are conducted and the results show that the air flow settings have significant impacts on the indoor environment controlled under limited cooling supply. Both control strategies can achieve significant improvements in the indoor temperature and humidity controls as well as significant fan power saving.

1. Introduction

1.1. Background of research and related studies

The real-time balance between supply and demand sides of a power grid is a critical system requirement [1]. Any power imbalance will cause severe consequences in the reliability and quality of power supply (e.g. power outages, voltage fluctuations) [2]. The latest example happened in Australia in February 2017. Due to huge demand caused by the highest outdoor temperature in history, the power grid faced with a great challenge and failed. Facing the challenge from power imbalance, smart grid is considered as a state-of-the-art technology to incorporate advanced technologies to offer better flexibility, reliability and security in grid operation [3–5]. The power control at the consumer side in response to grid requests (e.g., dynamic price and reliability information) is known as demand response (DR). DR programmes cannot only benefit the operation of power grids but also offer economic benefits to end-users [6–10].

Buildings play an important role in DR programmes by actively altering their load profiles during peak times. Moreover, with the help of advanced technologies such as building automation systems and smart meters, demand response control strategies in buildings could be implemented to realize a bidirectional operation mode between buildings and power grids [11–13]. When pricing changes are informed day ahead or hours ahead, demand shifting achieved by rescheduling the system operation, such as resetting the indoor air temperature, is a preferable alternative to reduce the power demand of air-conditioning systems. Lee and Braun [14] proposed three simple approaches for estimating building zone temperature set-point variations to minimize the peak demand during critical demand periods considering the peak demand reduction. Sun et al. [15] developed a demand shifting control strategy including building load prediction, cooling charging and

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discharging controls to reduce the building peak demand. Su and Norford [16] modulated the power demand of a central air-conditioning system by adjusting the supply chilled water temperature and hence the chiller power demand to satisfy the requirements of power grid. However, when adding an additional generation is extremely expensive or at the time of supply shortage, such conventional strategies are not sufficient to achieve significant demand reduction within a very short time, i.e., minutes, resulting from the inherent and significant delay of cooling charging and discharging control processes [17,18].

In fact, the power demand of chillers accounts for a large part of power use in commercial buildings using central air-conditioning systems [19]. Shutting down some of operating chillers in an air-conditioning system, which is a typical fast demand response and direct load control method, would be effective for urgent requests of smart grids. Due to the effectiveness of this fast demand response method for the urgent requests of smart grids, many studies have been conducted. The authors of this paper [20] pointed out that imbalanced chilled water distribution among a central air-conditioning system occurred after simply shutting down some of operating chillers. A cooling distributor based on adaptive utility function was developed to deal with this problem. They [21] also proposed a novel control concept (i.e., supply-based feedback control strategy) for DR events, instead of conventional control strategies commonly used for central air-conditioning systems, to effectively avoid the serious operation problems (e.g., imbalanced cooling distribution) and ensure the expected immediate power reduction after adopting such fast demand response method. Simultaneously, such fast demand response method has been applied in real projects, such as by CLP, a major utility company in Hong Kong [22]. During DR period, the indoor environment would be considered. When a DR strategy of an air-conditioning system is adopted to benefit the smart grids, indoor thermal comfort would be potentially sacrificed to unacceptable levels [23]. Zhang et al. [24] investigated 56 subjects' thermal comfort during DR conditions and pointed out that subjects' thermal comfort zone during DR events was wider than that predicted by Fanger's PMV/PPD model. Chu et al. [25] developed a reasonable DR program with a least enthalpy estimator (LEE)-based fuzzy thermal comfort controller of air-conditioning systems to control the fan-coil units. Results showed that the proposed method could ensure the indoor thermal comfort within the acceptable range. Although significant and immediate power reduction can be achieved by shutting down part of operating chillers, the indoor environment, particularly for the temperature and relative humidity, would be influenced obviously and thus essential to be considered.

1.2. Problem description and motivation of research

Currently, almost commonly-used automatic control strategies for central air-conditioning systems are demand-based feedback control. Such control logic can be managed properly in normal conditions when the total demand for each device is not more than the available cooling and all users can get what they need from their suppliers. However, when the cooling supply is not sufficient after part of operating chillers are simply shut down, the failure of conventional fan's control will occur. With limited cooling supply, the VAV dampers of indoor spaces would fully open and hence fans would operate at maximum speeds to maintain the original pressure set-points. The authors [26] pointed out such phenomenon (i.e., fully open VAV dampers and over-speeding fans) caused by the limited cooling supply using on-site measurements of a super-high commercial building. The excessive airflow circulated by full speeding of fans and cooled down by the limited cooling supply will lead to a serious increase of supply air temperature. Thus, the supply air with rather high temperature would almost lose the dehumidification ability. In the subtropical area such as Hong Kong, the humidity load in summer are always very high. In such a case, due to the unreasonable fan's control during DR events, not only the indoor air temperature (*T*) increases and deviates from the original set-point, but

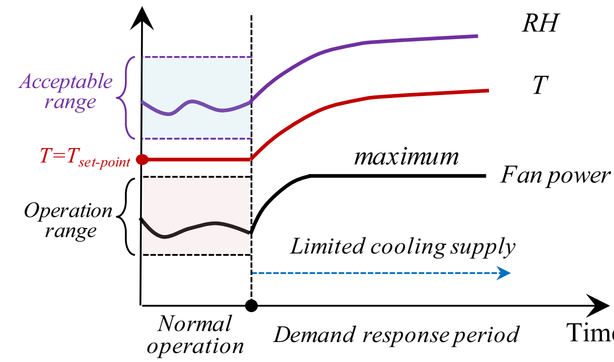

Fig. 1. Indoor air temperature and relative humidity with limited cooling supply.

also the relative humidity (*RH*) would increase seriously, as shown in Fig. 1. In normal conditions, the indoor air temperature is maintained at its set-point and *RH* fluctuates within an acceptable range. But during DR events (after shutting down part of operating chillers), the indoor environment would be worse and the fans operate at their maximum speeds.

In addition, much more power is consumed by the over speeding of fans and therefore potentially relieve the effect of DR control (i.e., power reduction). In fact, a pre-determined power reduction under a specific pricing incentive is signed ahead in the agreement with utility companies during a DR event [27]. In some mandatory incentive-based DR programmes, such as Interruptible/Curtailable (I/C) service, it is not economical and reasonable for end-users to prevent the unacceptable decrease of indoor thermal comfort at the expense of paying the penalty owing to unsatisfying the pre-determined power reduction. Therefore, under a pre-determined agreement on power use, rational use of limited cooling supply by optimizing the fan's control to achieve the best possible indoor environment would be a most effective and economical choice during DR events. This is the motivation of this study.

1.3. Outline of this research

This study, therefore, develops an online air flow optimization scheme to deal with above issues during DR events. The function of this scheme is realized by two strategies, a model-based optimal control strategy and an empirical near-optimal control strategy. The optimal control strategy is based on model-based prediction and genetic algorithm (GA) to modulate the air flow settings for individual AHUs (air handling units) during DR events. And the near-optimal control strategy achieves such online optimization using an empirical method. Although this near-optimal strategy cannot obtain obviously good indoor environment as that using the optimal strategy, it is simple and convenient for applications and has no specific requirement on control facilities (as illustrated in §2.3). This study contributes three main innovations, including: (1) optimal control and near-optimal control strategies are developed for DR events taking the indoor humidity into account in addition to the indoor air temperature; (2) air flow settings for AHUs are optimized to improve the indoor environment during DR events under a pre-determined power limiting threshold; (3) two control strategies are developed to satisfy different primary needs of building owners, i.e., best possible indoor environment and simply practical applications. Case studies are conducted to test and validate the performance of these two proposed control strategies as well as to quantify the impacts of air flow settings on the indoor environment (temperature and relative humidity) during DR events.