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Supply-based feedback control strategy of air-conditioning systems for direct load control of buildings responding to urgent requests of smart grids

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HIGHLIGHTS

- A new comprehensive concept/method, supply-based feedback control strategy, is proposed.
- An adaptive utility function with simplified parameter identification method is developed.
- Fast power demand response is achieved by shutting down some operating chillers directly.
- Problem of unbalanced cooling distribution among zones/spaces during DR can be solved.
- Significant power reduction is achieved using the supply-based feedback control strategy.

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ABSTRACT

Power demand response (DR) of buildings is considered as one of most promising solutions to power imbalance and reliability issues in smart grids while demand response control of air-conditioning systems is a most effective means. A fast demand response control strategy, direct load control by shutting down part of operating chillers, has received great attention in recent DR researches and applications. This method, however, would lead to uneven indoor air temperature rises among individual air-conditioned spaces due to the failure of proper distribution of limited cooling supply by the conventional demand-based feedback control strategy commonly used today. A novel supply-based feedback control strategy is therefore proposed to effectively solve the problems caused by the fast demand response and power limiting control strategy. This proposed strategy employs global and local cooling distributors based on adaptive utility function to reset the set-points of chilled water flow and air flow for each zone and space online. Simplified offline and online identification methods, for the two parameters respectively, ensure the convenience and robustness of the adaptive utility function in applications. Case studies are conducted on a simulated air-conditioning system to test and validate the proposed control strategy. Results show that the proposed control strategy is capable not only to maintain even indoor air temperature rises, but also to avoid the operation problems during DR events. Moreover, rather high indoor relative humidity is obviously decreased. The power rebound phenomenon is also relieved and the original comfort control of spaces can be resumed much quickly.

1. Introduction

The power balance between the supply side and the demand side of an electrical grid is a critical issue in the grid operation. However, the rapid growth of electricity demand and the integration of large amounts of renewable generations, which heavily depend on the weather conditions, impose huge stress on balance of electricity grid [1]. Any power imbalance can significantly affect the power reliability and quality, and even may lead to the grid failure if the grid balance fails to be recovered on time. Smart grid technology provides a promising solution for enhancing the balance of power grids by improving the ability of electricity producers and consumers to communicate with each other and make decisions about how and when to produce and consume electrical power [2]. The control of power demand at the consumer side in response to grid requests (e.g., dynamic price and reliability information) is known as demand response (DR). DR program, as one of

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Nomenclature

DR	demand response
BTM	building thermal mass
TES	thermal energy storage
PCM	phase change material
AHU	air handling unit
VAV	variable air volume
U	utility value
M	flow
T	temperature
R	cooling resource
n	total number of zones/spaces
Greek symbols	
λ	forgetting factor
ε	preset threshold
η	preset threshold
Superscripts	
k	number of iteration
Subscripts	
sp	set-point
tot	total
w	water
a	air
i	ith zone/space
out	outdoor

the most important means in the electrical grid management, has been promoted to encourage the end-users to change their load profiles under a specified pricing policy or request of the grid, which are dynamic or event-driven short-term modifications [3–5]. For instance, some Regional Transmission Operators (RTOs) and Independent System Operators (ISOs), such as Midwest ISO, New York ISO (NYISO) and ISO New England (ISONE), have allowed demand response resources (DRRs) to provide ancillary reserves to maintain the balance of electricity grids [6].

Buildings, as the primary energy end-users, could play an important role in power demand response in smart grids. Buildings consumed 74% of electrical energy in the USA [7] and over 90% of the total electricity in Hong Kong [8]. The interaction between buildings and the power grids could be very effective due to elastic nature of building energy use. The building demand management aims at minimizing the impact of peak demand charges and time-of-use rates on the service quality of buildings. Heating, ventilation, and air-conditioning (HVAC) systems, accounting for more than 50% of energy demand in buildings, are excellent demand response resources to reduce or shift the electricity demand during peak period, as well as their elastic nature [9]. In residential buildings, most of demand response management is to optimize the schedule of equipment operation to reduce the electricity consumption [10,11]. In contrast, the control method involved in commercial buildings during peak load period, which not only achieve economic benefits for building owners but also avail to the supply side of electricity grids, is complicated. Load shifting and load shedding are the two major means for peak load management in commercial buildings. Load shedding control reduces peak electric load in a building via turning off non-essential electrical load [12,13].

Compared with the load shedding, load shifting which is the process of shifting on-peak load to off-peak hours so as to take advantage of electricity rate difference in different periods is more commonly-used for demand side management in commercial buildings. Four typical categories of facilities are widely used for peak loading shifting, including: building thermal mass (BTM) [14–17], thermal energy storage system (TES) [18–21], combined use BTM with TES [22–24] and phase change materials (PCM) [25–28]. However, due to inevitable energy loss in the charging and discharging processes in peak load shifting, the peak load reduction is realized at the expense of the increased energy consumption. In addition, demand shifting control cannot achieve a significant immediate power reduction with a short time interval (i.e., minutes) resulting from the inherent and significant delay of charge and discharging control processes. This demand response controls, therefore, cannot fulfill the needs of the grid real time operation without any pricing information well in advance.

In fact, direct load control by shutting down some of the operating chillers in buildings can achieve immediate demand reduction, which has attracted the increasing attention of users. For example, the utility company (CLP) in Hong Kong has recently launched a pilot demand response programme, namely "Automated DR programme", which is actually a direct load control program. Shutting down some of chillers by the utility company automatically and remotely when there is an urgent need in power reduction is a major means for the direct load control for commercial buildings [29,30]. However, simply shutting down chillers at the cooling supply side will result in disorder of the entire air-conditioning system control because the control strategies commonly used in centralized air-conditioning systems today are demand-based feedback control [31]. Such demand-based feedback control strategies are based on the assumption that the cooling supply by chillers is set to be enough to fully satisfy the requirements of the terminal units (i.e., AHUs (air handling units)). If the cooling supply is far from sufficient, extremely serious operation problems would be caused, such as excessive speeding of chilled water pumps and air delivery fans, imbalanced chilled water distribution among AHUs, and imbalanced air distribution among VAV (variable air volume) terminals. These would result in very large differences of indoor air temperatures among different air-conditioned spaces and extra power consumption. Such operation problems may also relieve the demand reduction effect of DR control. In addition, the power rebound phenomenon is another serious problem right after DR events. The cooling demand during this period would be very high and individual air-conditioned spaces compete for the cooling supply to push their comfort levels to their original set-points. Thus, all the equipment in the air-conditioning system will be operated at full capacity and a huge stress will be boosted on the electricity grids during power rebound periods.

This study therefore addresses the fast demand response by limiting cooling supply directly allowing the commercial buildings to actively and effectively respond to short-term pricing changes or urgent requests from smart grids. In fact, a previous publication of the authors of this article presented a water flow supervisor based on adaptive utility function to effectively solve the problem of disordered water distribution in chilled water system under the reduced cooling supply [32]. However, that publication only addressed the basic concept and approach of supply-based feedback control and demonstrated/testified its application on chilled water systems. The comprehensive concept and common

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