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Cooling Supply-based HVAC System Control for Fast Demand Response of Buildings to Urgent Requests of Smart Grids

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Abstract

Shutting down part of operating chillers in HVAC (heating ventilating and air-conditioning) is a direct and effective mean allowing immediate responses of buildings to the power reduction requests of a smart grid.This paper presents a summary on the demand response control strategies and the problems when using the current conventional demand-based air-conditioning control strategies for fast demand response as well as the reasons of rebound problems after a DR event. The proposed cooling supply-based strategy aims at properly controlling air-conditioning systems when the cooling supply is not sufficient to fulfil the cooling demand of a building. This strategy can effectively solve problems of immediate power demand limiting control in response to the urgent requests of a smart grid as well as the rebound problems after the demand response event.

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Keywords: fast demand response;adaptive utility function;air-conditioning control;demand limiting;smart grid

1. Introduction

Power imbalance in power grid operation has become one of the most critical issues. 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 [1].Demand response (DR) program is promoted to encourage the end-users to actively alter their load profiles during peak times. Buildings, as the primary

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energy end-users, could play an important role on power demand response in smart grids. The interaction between buildings and the power grids could be very effective due to elastic nature of building energy use [2]. The building demand management for demand response aims at minimizing the impact of peak demand charges and time-of-use rates on the service quality of buildings. The HVAC system is an excellent demand response resource as the consumption of HVAC systems accounts for the largest part in buildings [3] as well as their elastic nature. Load shifting and load limiting are the two major means for peak load management. Demand limiting is the practice of restricting the peak power load of a building in such a way that the total power does not exceed the pre-defined peak load during periods of time where power is at a premium cost.

In smart grids, users can be informed of pricing changes or DR requests one day ahead, hours ahead or even minutes ahead depending on the prediction accuracy and the degree of emergency. When pricing changes are notified some hours ahead, rescheduling the system operation, such as resetting the indoor air temperature is a preferable alternative to reduce the air-conditioning power demand. When adding additional generation capacity is extremely expensive or at times of supply shortage, however, sudden pricing changes or urgent incentives are desirable alternatives to achieve the demand reduction within a very short time, i.e. minutes. In such a case, conventional building demand management strategies would not be sufficient.

In fact, shutting down some of the chillers can achieve immediate demand reduction [4]. However, simply shutting down chillers at the cooling supply side will result in disorder of the entire air-conditioning system control. Extremely serious operational problems would be caused, such as chilled water pumps running too fast, imbalanced chilled water distribution among AHUs (air-handling units), and imbalanced air distribution among VAV (variable air volume) terminals. This would cause extremely large difference of indoor air temperatures among different air-conditioned zones. This is because almost all the conventional control strategies used today for centralized air-conditioning systems are “demand-based” control strategies, in which the cooling supply by chillers is set to be enough to fully satisfy the requirements of the terminal units (e.g., AHUs). The water valve opening of individual AHU is modulated to maintain the supply air temperature at the preset set-point. The speeds of secondary pumps are adjusted to ensure the measured pressure drop of the main supply side (or the remote critical loop) at its set-point. For the individual AHU severing different rooms by different VAV boxes, the opening of each VAV box will be adjusted to maintain the air temperature of the room it serves. The chiller sequence/capacity will be properly controlled to meet the cooling load required. When the cooling supply is not enough, all cooling demand side users will compete for the limited cooling supply. The reductions in thermal comfort among different zones will not be even and the indoor environment in some zones will be sacrificed to unacceptable levels much more quickly. In addition, some other extremely serious operation problems would also be caused. For instance, secondary chilled water pumps would be over-speeded and the over-supplied chilled water flow rate of secondary loop would exceed that of primary loop (i.e. deficit flow in the bypass line).

This paper proposes a novel cooling supply-based control strategy that is able to properly control the air-conditioning system under the limited cooling supply conditions when shutting down some of chillers in commercial buildings in respond to short-term pricing changes/urgent requests from smart grids.

2. The proposed cooling supply-based control strategy

“Cooling supply-based” means that the control strategy aims at modulating the loads of the components (cooling demand side) properly in accordance to the reduced cooling supply from chillers (cooling supply side) during demand response event while providing the solutions to the inherent operation problems of commonly used control strategies. By introducing the concept of utility, an important concept in economics and game theory, a water flow distribution scheme and an air flow distribution scheme are developed.

2.1. Concept of utility value and development of adaptive utility function

In economics, utility function expresses utility as a function of the amounts of the various goods consumed, which establishes the relationship between goods consumed and people's satisfaction [5]. The problem concerned in this study is very similar to the utility concept in economics. An adaptive utility function is proposed to solve the problem concerning water/air flow distribution. The chilled water (or air) is the allocation resource, while the indoor thermal comfort in terms of the indoor air temperature is chosen as the utility value after normalization. In the following parts, the water flow distribution scheme is selected as the example to be developed based on the utility concept. The development process of the air distribution scheme is very similar, which is not given in this paper.

In this study, the case studies of demand response control are conducted in cooling mode. The utility value (U_i) of i^{th} zone can be defined as Eq.(1), which represents the degree of the satisfaction on the indoor thermal comfort.

$$U_i = 1 - \frac{|T_i - T_{set,i}|}{T_{band}} \qquad U_i \in [0,1] \tag{1}$$

where, T_i is the measured indoor air temperature of i^{th} zone. $T_{set,i}$ is the reference set-point (e.g. 24°C in this study) of indoor air temperature which is originally predefined during normal period. T_{band} is the maximum deviation between T_i and $T_{set,i}$, which is set as 10°C in this study. According to Eq.(1), a higher indoor air temperature means a lower utility value (i.e. less satisfaction) in cooling mode.

2.2. Adaptive utility function correlating indoor air temperature and water flow rate

The utility value (U_i) in Eq.(1) is defined as an index which represents the indoor air temperature in this study. The utility value can be assumed as a function of the chilled water flow rate. In fact, the indoor air temperature is affected also by a few other factors, such as the supply air temperature and cooling load. However, during a very short time interval, those factors can be considered unchanged and the correlation function (i.e., utility function) of fixed parameters between the indoor air temperature and chilled water flow rate is valid.

In this paper, a quadratic function is chosen as the form of the utility function, correlating the chilled water flow rate ($M_{w,i}$) supplied to each individual zone, as shown in Eq.(2). The selection of the utility function form is based on the study of the relationship between the water flow rate and the calculated utility value, which is not given in detail due to the space limitation. The adaptive method is used for updating $M_{U=1,i}$ online following the change of load condition in this study. Parameter a_i is also a variable depending on the cooling load conditions for certain zone. However, even a_i varies in a range, it has no significant impact on the calculation of the supply water flow rate set-point during DR event, thanks to the way of using the adaptive utility function and the updating of the other parameter, $M_{U=1,i}$. Therefore, constant values but different for different zones are predefined in this study.

$$U_i = -a_i (M_{w,i} - M_{U=1,i})^2 + 1, \qquad M_{w,i} < M_{U=1,i} \tag{2}$$

where, $M_{w,i}$ is the water flow rate supplied to i^{th} zone. $M_{U=1,i}$ is a fictitious reference value of the water flow rate which is required to maintain the indoor air temperature at its original set-point before DR event. a_i is a parameter representing the thermodynamic characteristics of the zone.

2.3. Online parameter updating of the adaptive utility function and water flow set-point prediction

The parameter, $M_{U=1,i}$ in Eq.(2), is assumed to be a constant within a small range of working condition and a short time interval, but it is regarded as a slowly-varying coefficient, allowing the function to be an adaptive utility function. The value of this parameter at current time step k is determined by the current water flow rate and utility value as shown in Eq.(3). To illuminate the impact of the measurement uncertainty and fluctuation, the simple data filter using a forgetting factor is applied to the updated $M_{U=1,i}$ as shown in Eq.(4). λ is the forgetting factor selected to be 0.95 in this study. Having the updated $M_{U=1,i}$, the utility function can be used to estimate the water flow rate needed to achieve any target utility value for a zone after rewriting, as shown in Eq.(5).

$$M^{k}_{U=1,i} = M^{k}_{w,i} - \sqrt{\frac{1-U^{k}_{i}}{a_i}} \tag{3}$$

$$M^{k}_{U=1,i} = \lambda M^{k-1}_{U=1,i} + (1-\lambda) M^{k}_{U=1,i} \tag{4}$$

$$M^{k}_{sp,i} = M^{k}_{U=1,i} + \sqrt{\frac{1-\bar{U}^{k}_{sp}}{a_i}} \tag{5}$$

where, $U^{k}_{sp}$is the target utility value of all zones at current time step, which is the expected utility value of all zones if the temperatures (utility values) of all zones are controlled to be the same and the available cooling capacity is fully used.

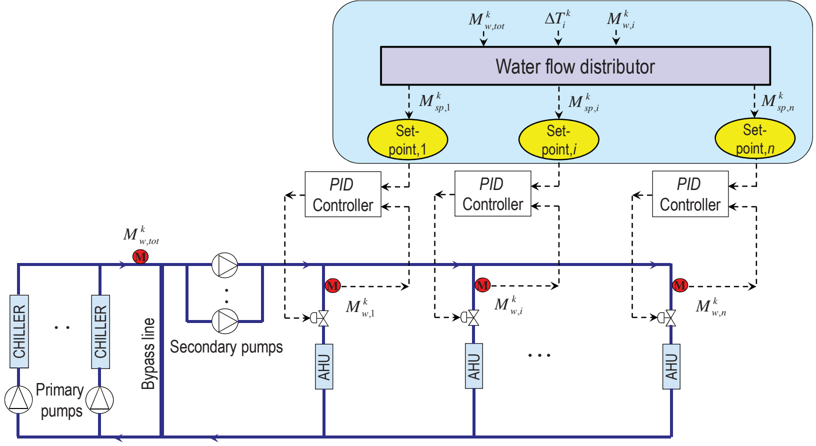

Fig. 1 Proposed chilled water flow control strategy

As shown in Fig. 1, the chilled water flow distribution scheme employs a supervisor (namely water flow distributor) to continuously adjust the set-points of chilled water flow rates of individual zones. At each time step, the set-points are reset aiming at maintaining the same indoor air temperature rise, i.e. the same utility value, among different zones, as illustrated by Eq.(6). At the same time, the constraint given by Eq.(7) should be satisfied in order to prevent the water flow rate of the secondary loop exceeding that of the primary loop.

$$\sum_{i=1}^{n}(U_i - \bar{U}_i)^2 = 0 \tag{6}$$

$$\left|\sum_{i=1}^{n} M_{sp,i} - M_{w,tot}\right| < \varepsilon \tag{7}$$

3. Results and discussions

3.1. Setup of test platform

In this study, a virtual test platform is built to test the proposed fast demand response and power limiting control strategy using dynamic models developed on TRNSYS. The weather data adopted is a typical summer day in Hong Kong. The original indoor air temperature set-point before DR event is 24°C. The DR period is between 15:00pm and 17:00pm.The simulated central chiller plant is a typical primary constant-secondary variable chilled water system. It consists of six identical chillers with rated capacity of 4080 kW. Each chiller is associated with a primary chilled water pump of constant speed (172.5 L/s). Six air-conditioned zones in a commercial building have different sizes and different cooling load profiles. In the test, there are four operating chillers before the start of the DR event, and two of the operating chillers are shut down and two chillers remain to operate.

3.2. Case 1: Results of the case study on chilled water distribution

In Fig. 2(a) using conventional control strategy, the indoor air temperature profiles of the six zones are obviously different not only during but also right after DR event. Using the proposed control strategy, the temperature profiles of the six zones are almost the same during the DR event when the cooling supply from chillers is limited and have a similar resume speed to their original set-points after DR event, as shown in Fig. 2(b). As shown in Fig.3 (a), the proposed control strategies could eliminate the deficit flow (which occurs seriously under conventional control strategy) and keep the water flow rate in bypass line about zero during DR period.

Fig. 3(b) compares the power consumptions when using the two control strategies, including the electricity use of the primary/secondary chilled water pumps and the chillers. During the DR event, the proposed control strategy achieved a power reduction about 1350 kW, accounting for 39% of the power before the start of DR event. Compared to the conventional control strategy, the power is further reduced by about 380 kW (11.2%) using the proposed control strategy mainly due to the power reduction of the secondary pumps. The energy savings during DR event is about 760 kWh (15.3%) using the proposed control strategy.

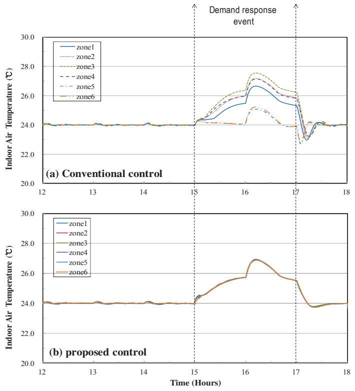

Fig.2 Indoor air temperature profiles of zones in DR tests in case 1

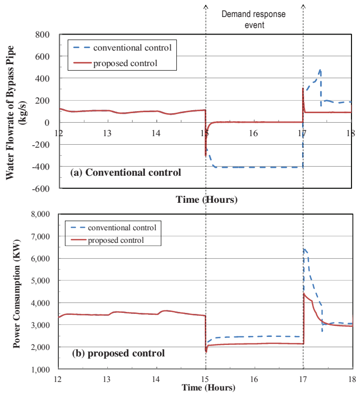

Fig.3 Water flow and power in DR tests in Case 1

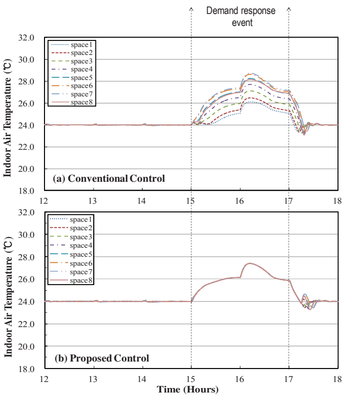

Figure 4 Results of different spaces served by one AHU in Case 2

It is worth noting that an obvious rebound phenomenon can be observed after DR event when conventional power limiting strategy is used as shown in Figure 3(b). It reflects the operation when the proposed control is released right after the DR event and the conventional control strategy is resumed. The cooling demand will be very high and individual zones will compete for the chilled water again to push their comfort levels to their set-points. To avoid these problems, the proposed power limiting control strategy is set to continue until the indoor air temperatures of all zones reach their original set-points after DR period. Besides, the number of chillers (i.e., four) to be activated is the same as that right before the DR event, instead of all chillers.

3.3. Case 2: Results of the case study on air flow distribution

Another case study was conducted to evaluate the performance of air flow distribution scheme when each of the 6 zones in the test platform is divided in 8 spaces severed by 8 VAV boxes respectively. Similarly, as shown in Fig. 4(a), when using the conventional control strategy, the measured air temperature of each space is quite different among different spaces during DR event. When using the proposed control strategy involving the air flow distribution scheme, the space temperature profile during DR event experienced almost the same changing trend.

4. Conclusions

A novel fast demand response and power limiting control strategy is developed which achieves quick power reduction by properly shutting down some of the chillers. Water (air) flow distributors based on adaptive utility function are developed to properly distribute the chilled water among different AHUs and air flow among different VAV boxes to maintain uniform thermal comfort sacrifices in the different zones or spaces during a DR event.

Test results show that the proposed control strategy can achieve fast power reduction when receiving the demand response request. Simultaneously, the proposed control strategy can effectively solve the disordered water (air) distribution problem and achieve the uniform changing profiles of the thermal comfort among different zones under the limited cooling supply. The deficit flow problem also can be avoided.

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Biography

Prof. Shengwei Wang is a chair professor. He is research interests and application experiences are on building energy and intelligent buildings in the subject areas including: building system dynamic simulation, building and HVAC system diagnosis, HVAC&R system energy efficient and optimal control, HVAC&R and energy system optimal design, building Demand Response method for smart grid, smart energy system for smart towns, and intelligent building technology.