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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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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.

Keywords: fast demand response, smart grid, supply-based feedback control, adaptive utility function, direct load control, building demand management.

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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 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 methodology of supply-based feedback control were not established. The general approach of supply-based feedback control for systems of multiple levels was not developed. The generally applicable parameter identification method of the strategy and the control of humidity were not addressed. In this article, these essential aspects are further addressed and developed on the basis of previous work. Firstly, a comprehensive concept of supply-based feedback control strategy and associated common methodology are developed and presented. This control strategy properly controls the distribution of limited cooling supply among users proactively based on the comfort feedback conditions from air-conditioned spaces and provides a solution to the inherent operation problems of commonly-used demand-based feedback control strategies. Secondly, the proposed control 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 while based on the monitored states finally achieved in different zones and spaces to establish the feedback mechanism. Thirdly, the global cooling distributor for chilled water system and the local cooling distributors for air-side systems, for practically realizing the proposed supply-based feedback control for systems of multiple levels, are developed and validated. Furthermore, a simplified practically applicable offline and online identification methods are developed to identify the two parameters of the utility function respectively. Finally, the problem of high indoor relative humidity occurred under limited cooling supply is considered. Case studies are conducted on a simulated air-conditioning system including the water and air sides to test and validate the proposed control strategy. The control performance of the proposed supply-based feedback control strategy is evaluated and compared with that using the conventional demand-based feedback control strategy during a DR event.

2. Problems of conventional demand-based feedback control in DR events and concept of proposed supply-based feedback control

Almost all the automatic control strategies commonly-used today for air-conditioning systems in buildings are demand-based feedback control. The control mechanism of typical demand-based feedback control of an air-conditioning system in a building is shown in Fig.1. The regulators, typically PID controllers, modulate the cooling intakes from their suppliers to maintain the states of the spaces served by the terminal units (or states of AHU outlets) at their set-points.

The control of cooling distribution in an air-conditioning system is based on the cooling demands of individual air-conditioned spaces, i.e., demand-based feedback control. The cooling generated by chillers is delivered to the cooling demand side (i.e., indoor spaces) based on their cooling loads. Each AHU and its regulator form a local feedback control loop, which controls the cooling (i.e., chilled water) taken from its supply side (i.e., chillers) based on what needed by the terminal units served by the AHU, typically controlling the supply air temperature at the expected value (i.e., set-point). Such control assumes that all AHUs can get what they need from chillers. In fact, it is the case as the control of chillers is also based on the demands of the AHUs they serve. Similarly, the cooling (i.e., air flow) taken by each terminal unit from its supply side (i.e., AHU) is also based on what needed by space it serves, typically controlling the space air temperature at its set-point. Again, this control is based on the assumption that all terminal units can get what they need from AHUs. The distribution of the cooling in a building is therefore managed based on those standalone demand-based feedback control loops.

The distribution of the cooling based on the demand-based feedback control loops can be managed properly in normal conditions while the total demand to each device is not more than what it can provide and all users can get what they need from their suppliers. However, after shutting down some of operating chillers during DR events, the cooling supply is limited and not enough to meet the cooling demand of the building. Serious unbalanced cooling distribution and system operation/control problems would occur both at the water side and the air side of the air-conditioning system. With limited cooling supply, all cooling devices at demand side (e.g., AHUs and VAV boxes) would compete for the limited cooling supply. The modulating valves/dampers of most cooling devices at their demand side will be fully opened quickly as they could not maintain the controlled variables at their set-points. The cooling distributions both among water side users (i.e., individual zones) and air side terminal units (i.e., individual spaces) will not be evenly reduced, which would lead to the indoor environments in part of zones/spaces sacrificing to unacceptable levels much more quickly than other zones/spaces. The high supply air temperatures of AHUs would also cause the relative humidity in certain spaces beyond the comfortable range seriously. In addition, secondary chilled water pumps at the water side and supply fans at the air side would be operated at full speed. It is due to the need to maintain the preset differential pressure by secondary chilled water pumps and the static pressure by supply fans in the condition of fully opened valves. The excessive speeding of secondary chilled water pumps and air delivery fans would result in significantly increased power consumption and relieve the effects of DR control on power reduction. Furthermore, right after DR events, namely power rebound period, similar operation problems would occur again until the air-conditioning system resumes to the normal condition.

A completely new control concept, supply-based feedback control strategy, is proposed to solve the inherent operation problems effectively during DR events and rebound periods as shown in Fig.2. At the chilled water side, the supply-based feedback control (i.e., global cooling distributor) manages the distribution of the total available chilled water (i.e., total cooling supply) among the individual zones based on the measured average space temperatures of all zones aiming at keeping space temperatures of all zones the same (rising gradually during DR events). Similarly, at the air side, the supply-based feedback control (i.e., local cooling distributor) manages the distribution of the total available cooling supply of an AHU among the individual spaces based on the measured space temperatures of all spaces in the zone aiming at keeping temperatures of all spaces the same.

Same to the conventional (demand-based) feedback control strategies widely used today, the supply-based control strategy also based on the actual measurements as the feedback to ensure the accuracy, adaptiveness and simplicity of cooling distribution as it is hard for a simple predictive control to achieve the same control performance due to the complexity and every change of conditions and disturbance factors. In fact, major difference compared with the conventional control strategies is that all the feedbacks are from the end-user side (i.e., space indoor temperature) rather than from their immediate outlets (e.g., outlet air temperatures of AHUs).

3. Proposed fast demand response and power limiting control strategy

Compared with traditional power grids, smart grids enable a bidirectional operation (i.e., "two ways" connection with power flow and information flow) to improve power reliability and energy performance. Buildings are the major energy consumers today and their shares are still increasing due to the urbanization. Buildings can benefit power grids by relieving the pressure of power imbalance in different energy processes. Due to the advanced technologies such as building automation systems and smart meters, the demand response control strategies in buildings could be implemented to realize this bidirectional operation mode between power grids and buildings. Fig.3 illustrates the technology infrastructure for implementation of the fast building demand response method supported by the proposed supply-based feedback control, which establishes the communication and interaction between building automation systems of (commercial or non-residential) buildings and smart grids via smart meters. The smart meters are the interface or bridge for the communication between a power grid and buildings to achieve interaction and optimization.

When there is an urgent DR request from a smart grid (e.g., sudden price incentive or power reduction request), a fast demand response and power limiting control strategy is proposed to achieve an immediate power reduction by proper control of the air-conditioning systems in buildings. A schematic of the control strategy is shown in Fig.4. Once a DR request is received from the grid, a power demand optimization module, based on the incentive and using the building power demand predictor, determines the power limiting threshold and system alternative settings during the DR event, including the numbers of chillers and secondary pumps to be shut down and fan speeds as well. With the power limiting threshold and instantaneous power demand measured by the power meter, the chiller load regulator fine-tunes the chiller power consumption by adjusting the chilled water flow. The purpose of using this chiller load regulator is to adjust the power consumption of the air-conditioning system allowing the total building power consumption within preset limiting threshold. According to the total cooling that can be delivered to users, cooling distributors are used to distribute the cooling supply using the developed supply-based feedback control strategy instead of conventional demand-based feedback control strategy. At the water side, the global cooling distributor determines the distribution of chilled water to individual AHUs (i.e., zones) based on the measured temperatures of return air to AHUs. At the air side, for each zone, a local cooling distributor is used to determine the distribution of supply air flow to individual VAV boxes (i.e., spaces) based on the measured return air temperatures of the spaces. This paper focuses on the newly proposed supply-based feedback control of air-conditioning systems at both the water and air sides, which solves the inherent problems of conventional demand-based feedback control of air-conditioning systems when the fast demand response and power limiting control strategy is implemented. The development and use of the building power demand predictor [16], power demand optimization [16] and chiller load regulator [33] can be found in previous publications.

4. Cooling distributor based on adaptive utility function

With limited cooling supply in a building when some essential operating chillers are shut down, the cooling distributors are responsible for managing the cooling distribution among individual air-conditioned spaces to realize even reduction of the comfort level. As shown in Fig.2 and Fig.4, a global cooling distributor is employed at the chilled water side while a local cooling distributor is employed at the air side and the working principles of these two cooling distributors are similar. It is worth noticing that more or less levels of cooling distributors could be employed according to the configuration of the air-conditioning system in a building. Fig.5 explains the basic mechanism in managing the distribution among *n* zones. Generally, *n* zones should reach a uniform target value of thermal comfort index constrained by the total cooling resource provided. Compared with the target value determined, the cooling allocated to zones (e.g., 1, 2) with lower thermal comfort index should be increased while the cooling allocated to the zones (e.g., n) with higher thermal comfort index should be reduced. The change of cooling to each zone is determined by the difference between the target value and the current value of its thermal comfort index (i.e., ΔU). This process is similar to the resource distribution issue according to one's need with limited resource based on the utility concept in economic field. "Utility" represents satisfaction experienced by the consumer of a good. Utility function expresses the utility as a function of the amount of the resource consumed [34]. This concept is commonly used in economics field. It is also used in many other areas besides economics. For example, utility function is widely used in wireless resource management, such as bandwidth allocation [35, 36]. This concept is also adopted to solve the operation problems in air-conditioning systems [32].

In this study, the utility value is the thermal comfort index and utility function describes the relationship between the thermal comfort index and the cooling supply allocated. The cooling distributor based on adaptive utility function is developed to achieve supply-based feedback control strategy of an air-conditioning system during a DR period, while adaptive utility function is proposed to update one of the two parameters of the utility function online for better accuracy and simplicity of parameter identification.

4.1 Concept of utility value

In this study, the utility value represents the thermal comfort simply represented by the indoor air temperature, as illustrated in Eq.(1).

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

where, U_i is the utility value of i^{th} zone/space, T_i is the measured indoor air temperature of i^{th} zone/space. $T_{set,i}$ is the reference set-point (i.e., 24°C in this study) of indoor air temperature which is predefined for normal operation. T_{band} is a very large deviation between T_i and $T_{set,i}$, which should be large enough to fully cover the whole possible indoor temperature range of spaces during DR events. Its value is set to be 10°C in this study.

4.2 Concept of adaptive utility function

The chilled water flow at the water side or air flow at the air side are the allocated resources for each zone or space, and utility function is defined as Eq.(2) [32].

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

where, M_i is the chilled water/air flow rate supplied to i^{th} zone/space. $M_{set,i}$ is a fictitious reference value of the water/air flow rate which is required to maintain the indoor air temperature at its original set-point before DR events but under current cooling load condition. a_i is a parameter representing the thermodynamic characteristics of i^{th} zone/ space.

In fact, the utility value (i.e., indoor air temperature) is also affected by a few other factors, such as the supply air temperature. However, during a very short time interval, those factors can be considered unchanged and the utility function with fixed parameters correlating the indoor air temperature with chilled water flow or air flow is valid. To allow the use of the utility function over the entire working range during a DR event, one of the two parameters of the utility function is updated online and the adaptive utility function is employed.

4.3 Parameter identification of adaptive utility function

In adaptive utility function, two parameters, $M_{set,i}$ and a_i, are needed to be determined before application. $M_{set,i}$ is identified and updated online and a_i is identified offline prior to application.

Offline identification of parameter a_i

The parameter a_i for i^{th} zone/space is identified prior to online application. Although 'a_i' is not a constant coefficient and changes due to the change of cooling load, it has no significant impact on the actual control performance of the water/air flow distribution among individual zones/spaces during DR events. This is because of the way of using the adaptive utility function (i.e., online updating of the other parameter, $M_{set,i}$), which is demonstrated in section 6. Therefore, constant values but different for individual zones/spaces are predefined in this study.

In principle, 'a_i' varies mainly due to the changes of cooling load, which can be roughly estimated by the chilled water flow or air flow. The identification method developed in the previous study [32] is not convenient for practical application. A very simple identification method, therefore, is developed because of the robustness of the utility function with an inaccurate 'a_i'. Based on the utility function (i.e., Eq.(2)), 'a_i' can be used to present the change of indoor air temperature corresponding a change of chilled water flow (or air flow) at current cooling load, as shown in Eq.(3).

$$a_i = \frac{\Delta T_i}{10 \times \Delta M_i^2} \tag{3}$$

$$\Delta T_i = (T_{out,i} - T_{set,i}) + 5 \tag{4}$$

where, ΔT_i is the indoor air temperature rise (stabilized) of i^{th} zone/space when the air-conditioning system is shut down. ΔM_i is the chilled water flow rate/air flow just before shutting down the air-conditioning system. To have a better reliability and simplify the identification process, the system design data are used. For identifying 'a_i', when the air-conditioning system is working, the indoor air temperature is assumed to be its design value. When the air-conditioning system is off, the indoor air temperature is assumed to be 5℃ higher than the design outdoor air temperature ($T_{out,i}$). Then, ΔT_i can be calculated by Eq.(4).

Online parameter identification of $M_{set,i}$

Having the parameter "a_i" as a constant, the value of $M_{set,i}$ at current time step k is determined by the current measured chilled water/air flow rate (M_i^k) and utility value (U_i^k), as shown in Eq.(5). In practical applications, the field measurements always have obvious noise and fluctuation. To solve this problem, a simple filter using a forgetting factor is applied to smooth the updated parameter, $M_{set,i}$, as shown in Eq.(6). Having the updated parameter ($M_{set,i}$), the utility function can be used to estimate the water/air flow rate needed to achieve any target utility value for a zone/space after rewriting Eq.(2) as shown in Eq.(7).

$$M_{set,i}^{k} = M_{i}^{k} + \sqrt{\frac{1-U_{i}^{k}}{a_{i}}} \tag{5}$$

$$M_{set,i}^{k} = \lambda M_{set,i}^{k-1} + (1-\lambda) M_{set,i}^{k} \tag{6}$$

$$M_{sp,i}^{k} = M_{set,i}^{k} - \sqrt{\frac{1-\bar{U}_{sp}^{k}}{a_{i}}} \tag{7}$$

where, $\bar{U}_{sp}^{k}$ is the target utility value of all zones/spaces at current time step, which is the expected utility value if the temperatures of all zones/spaces are controlled to be the same. λ is the forgetting factor selected to be 0.95 in this study

4.4 Overall procedure of cooling distribution

A global cooling distributor and a few local cooling distributors are developed to continuously update the set-points of chilled water flows to different zones and air flows to different spaces within zones, respectively. 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/spaces, as illustrated in Eq.(8). For the chilled water distribution, the total chilled water flow distributed is set to be equal to that in the primary loop, which can fully take advantage of the cooling supply and prevent the deficit flow problems, as shown in Eq.(9). The water flow rate of each AHU (zone) is controlled at the given set-point from the global cooling distributor by modulating the flow control valve based on a feedback (PID) control (see Fig.4). At the air-side, the speed of supply fan and the total air flow rate are kept at the same as that at the start of DR events, which can prevent the increased fan power consumption and maintain the relative humidity of spaces not too high. This also avoids offsetting the power reduction at the water side during DR events and relieving the effect of DR control. Thus, the air flow distributor should meet the constraint, that is, the sum of air flow rate distributed to individual spaces should be equal to the total air flow rate to be distributed, as shown in Eq.(10). The air flows of the VAV boxes are then controlled at their set-points determined by their local cooling distributors by modulating the air dampers.

$$\sum_{i=1}^{n}(U_i - \bar{U}_i)^2 = 0 \quad (8)$$

$$|\sum_{i=1}^{n} M_{sp,w,i} - M_{w,tot}| < \varepsilon \quad (9)$$

$$|\sum_{i=1}^{n} M_{sp,a,i} - M_{a,tot}| < \eta \quad (10)$$

where, U_i is the utility value of i^{th} zone/space at a time step. $\bar{U}_i$ is the average utility of all zones/spaces. n is the total number of zones/spaces. $M_{sp,w,i}$ is the chilled water flow rate set-point of i^{th} zone at current time step. $M_{w,tot}$ is the total available chilled water flows in the primary loop. $M_{sp,a,i}$ is the air flow rate set-point of i^{th} space at current time step. $M_{a,tot}$ is the total air flow to be distributed in a zone. ε , η are the preset thresholds.

4.5 The process of cooling distribution

At the start of a time step, the current state variables, including: the indoor air temperatures of individual zones ($T_{w,i}^{k}$) and spaces ($T_{a,i}^{k}$), the water flow of each zone ($M_{w,i}^{k}$) and the total water flow provided in the primary loop ($M_{w,tot}^{k}$) for the global cooling distributor, the air flow of each space ($M_{a,i}^{k}$) and the total air flow supply ($M_{a,tot}^{k}$) for the local cooling distributors, are collected. Fig.6 shows the computation flow chart of the local cooling distributor for the air side system in a zone associated with one AHU. The utility value of each space ($U_{a,i}^{k}$) is calculated based on the definition (Eq.(1)). Then, the parameter ($M_{set,i}^{k}$) of the utility function for each space is updated online using the current utility value and actual air flow (Eq.(5)), followed by a data filter (Eq.(6)). The average of the actual utility values of all spaces within the zone is used as the initial control target value for all spaces and the air flow rate set-point ($M_{sp,a,i}^{k}$) of each space is determined using the updated utility function (Eq.(7)), which correlates the utility value and air flow rate of the space. Finally, a flow limit check and fine-tune scheme is employed to check whether the sum of the calculated air flow rate set-points ($\sum_{i=1}^{n} M_{sp,a,i}^{k}$) is equal to the actual total available air flow rate ($M_{a,tot}^{k}$). If the $\sum_{i=1}^{n} M_{sp,a,i}^{k}$ is no equal to $M_{a,tot}^{k}$, the target utility value ($\bar{U}_{sp,a}^{k}$) will be fine-tuned by adding or subtracting a predefined incremental (Δv). The updated target utility value is then used to calculate the air flow set-points again until the difference between the sum of air flow set-points and the actual total flow rate is within a preset threshold (η). The final air flow rate set-point ($M_{sp,a,i}^{k}$) of each space is then set as the set-point for the air flow control of the VAV box.

The computation process of the global cooling distributor for managing the water distribution at the water side is the same, except the measurements ($M_{a,tot}^{k}, M_{a,i}^{k}, T_{a,i}^{k}$) at the air side are replaced by the measurements ($M_{w,tot}^{k}, M_{w,i}^{k}, T_{w,i}^{k}$) at the water side respectively.

After DR events, the proposed control strategy is not released until the indoor air temperatures resume to their original set-points. This can maintain the indoor air temperature at nearly same recover speed and particularly avoid the secondary pumps and fans operated at full capacity due to the high cooling demand in rebound period.

5 Test platform

Computer-based dynamic simulation is adopted, as an effective mean, to test and validate the online control strategies. 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 [37]. This test platform employs detailed physical models including the building envelop and major components (e.g. chillers, pumps, fans, hydraulic network, air ducts, AHUs) of a central air-conditioning system. The dynamic processes of heat transfer, hydraulic characteristics, water flow and air flow balance scheme, energy conservation and controls among the whole system are simulated.

The central chiller plant used in the study is a typical primary constant-secondary variable chilled water system. It consists of six identical chillers with rated capacity of 4080 kW and two secondary water pumps. The cooling source for the building comes from the chilled water circulating in the AHUs which cooled down the supply air temperature to a predefined set-point. The building is a high-rise building simulated by a multi-zone model (Type 56) in TRNSYS. Six air-conditioned zones with different cooling load profiles in this building cooled by six AHUs are selected to demonstrate the water side cooling distribution and control strategy.

Considering the air side, a VAV system in one of the six zones served by one AHU is simulated in detail, which consists of a supply and a return fan with rated capacity 34 kW and 32 kW respectively. The VAV system contains eight spaces with different cooling load profiles and air duct resistance is also concerned. The design supply air static pressure is 650 Pa and fresh air flow set-point of this system is set to be a constant value according to the ASHRAE Standard 62.1-2013.

The office hour of the building is between 08:00am and 18:00pm and the DR period is two hours between 15:00pm and 17:00pm in a summer day in Hong Kong. The original indoor air temperature set-point in normal condition is set to be 24℃. In the test, there are four operating chillers before the start of the DR event, and two operating chillers are shut down at the start of the DR event and two chillers remain to operate.

6 Results and Discussions

6.1 The robustness of parameter a_i

Four test cases were conducted to test and validate the impact of parameter a_i on the robustness of the adaptive utility function in online applications. The values of 'a_i'

in Case 1 was determined based on the method described a previous study [32]. In Case 2, the values were estimated by simplified approach, i.e., using Eq.(3), and the values of a_i in the other two cases were selected to be very different from the relatively accurate values (i.e., identified in Case 1). Because the working mechanism of the cooling distributors for the air side was similar to that for the water side, this case study was carried out at the water side only. The test platform used was described in section 5. The values of 'a_i' in the four test cases are listed in Table 1.

The results of the four test cases are shown in Fig.7. In Case 2, although the values of parameter a_i of some zones were seriously deviated from the estimated values, the controlled indoor air temperatures of the six zones experienced slight different at the start of the DR period, then quickly approached the very similar profiles within very short time and last during the whole DR event. Although the values of 'a_i' of certain zones had very significant changes, the indoor air temperature profiles in Case 3 and Case 4 were affected noticeably but the differences between the controlled indoor air temperature profiles of different zones were very small and acceptable for practical applications. It can be concluded that the control strategy is not sensitive to the value of parameter a_i due to the use of the adaptive utility function (compensation of updated parameter M_{set}). Therefore, due to the robustness of parameter a_i, it is acceptable to determine the parameter a_i offline using the simplified estimation method for practical applications.

6.2 Test and validation of cooling distributors

The use of cooling distributors for the supply-based feedback control strategy not just effectively solves the unbalanced distribution problems occurred at the water side and air side of an air-conditioning system during DR events, but also achieves further power reduction by diminishing the operation problems of secondary water pumps and air delivery fans. In addition, the power rebound phenomenon right after DR events is also effectively relieved.

Test results on the chilled water system

Fig.8 shows the comparison among the indoor air temperature profiles of the six zones using the conventional demand-based feedback control and the proposed supply-based feedback control strategies. In Fig.8(a), using the conventional demand-based feedback control, the indoor air temperature profiles of the six zones are obviously different not only during the DR event, but also right after the DR event. This was mainly because right after the DR event, the cooling demand was very high and individual zones competed for the chilled water again to push their comfort levels back to their original set-points. If the proposed control was released right after the DR event and the conventional control strategy was resumed accordingly, the unbalanced indoor air temperature rises among individual zones would happen again.

In Fig.8(b), it can be observed that the temperature profiles of the six zones are almost the same during the DR event using the proposed control strategy when the cooling supply from chillers is limited and have the similar resume profiles after the DR event. The indoor air temperature at 16:00pm had an obvious jump because there was a significant step change introduced on the solar radiation at 16:00pm. This can demonstrate the robustness of proposed control strategy based on adaptive utility function when facing sudden significant changes of cooling loads. After the conventional feedback control was resumed when the indoor air temperature approached their original set-points, the profiles experienced a little differences among individual zones as the results of the handover between the control strategies.

Fig.9 presents the actual chilled water flow rates distributed to six individual AHUs using the conventional demand-based feedback control and the supply-based feedback control strategies. During and right after the DR event, the proposed supply-based control strategy achieved stable and proper chilled water distribution among six zones, avoided the disordered water flow distribution effectively and maintained the same indoor air temperature profiles among different zones, as shown in Fig.8(b). In Fig.9(a), using the conventional control strategy, the water flow rates were very high and out of control due to the competition among the zones. Fig.10 shows the chilled water flows in the by-pass line using the conventional demand-based feedback control and the proposed supply-based feedback control strategies. The proposed control strategy could eliminate the deficit flow and keep the water flow rate in the by-pass line about zero during the DR event while there was serious deficit flow when using the conventional strategies.

Test results on air-side system

Fig.11 shows the indoor air temperature profiles of eight spaces using the conventional demand-based feedback control and the proposed supply-based feedback control strategies. In Fig.11(a), the indoor air temperature profiles of the eight spaces were obviously different both during and right after the DR event. This was mainly because the cooling demand was very high right after the DR event and the individual spaces would compete for the air flow again after the DR event to push their comfort levels back to their original set-points. When the proposed control strategy was adopted, the temperature profiles of the eight spaces were almost the same during the DR event with the limited cooling supply from chillers and also had a similar resume profiles after the DR event, as shown in Fig.11(b). The slight fluctuation was caused by handover between the control strategies after the indoor air temperatures of eight spaces resumed to their original set-points.

Fig.12 shows a comparison of the indoor relative humidity of the eight spaces using the conventional demand-based feedback control and the supply-based feedback control strategies. During the DR event, using the conventional control, the relative humidity of these spaces increased seriously and the maximum value reached nearly 83%, which was much higher than the acceptable range of indoor air relative humidity. Moreover, the significant differences among spaces were primarily caused by the unbalanced air flow distribution. Although the relative humidity was not the main control objective of the proposed control strategy, the relative humidity of spaces did not increase as high as that using the conventional control, and amounts of increase in some spaces were over 10% less (i.e., reduced from 83% to 72%). It was benefited from the supply fans control. During the DR event, the supply fan was set to be nearly the same speed as that right before the DR event instead of running at full speed. In this case, the supply air temperature would not increase so high due to the decreased total air flow rate by limiting the speed of the supply fan. The control strategy was not switched to the conventional control strategy until the indoor air temperatures of spaces got right. Fig.13 presents the air flow rates distributed to individual spaces using the conventional demand-based feedback control and the supply-based feedback control strategies. During and right after the DR event, the proposed supply-based control strategy achieved stable and proper air flow distribution among eight spaces, avoided the disordered air flow distribution effectively and maintained the same indoor air temperature profiles among different spaces, as shown in Fig.11(b).

Power consumption of the air-conditioning system

The primary objective of the DR control is to achieve power reduction as much as possible. Shutting down some of the operating chillers directly might be failure to realize a fast power reduction if the whole air-conditioning system is still controlled by the conventional demand-based feedback control strategies. Fig.14 compares the total power consumptions using the two control strategies, including the chillers, the (primary and secondary) water pumps and the (supply and return) fans. It can be observed that, using the conventional demand-based feedback control, the extra power consumption caused by full speed operation of the secondary pumps and fans almost offsets the effect of shutting down chillers. This phenomenon was more seriously compared with the result presented in the previous publication of the authors [32] since only the power effect of full speed operation of secondary pumps (excluding the fans in air-side) was considered there. During the DR event, the proposed control strategy could achieve a power reduction about 1200 kW, accounting for 24% of the power consumption compared with that right before the start of the DR event, while there was almost no power reduction (even increased) due to the compensation of increased power consumption of pumps and fans when using the conventional demand-based feedback control strategies. In addition, it is worth noticing that an obvious rebound phenomenon can be observed after the DR event when the conventional demand-based feedback control strategy was used. Right after the DR event, the cooling demand was very high as individual zones/spaces competed for the provided cooling again to push their comfort levels back to their original set-points. The proposed power limiting control strategy was used during and after the DR event until the indoor air temperatures of all zones/spaces reached their original set-points. Besides, the number of chillers (i.e., four) was resumed to be the same as that right before the DR event, instead of all chillers. As a result, the power rebound was reduced by a significant amount, i.e., about 3600kW, which was 35.4% of the original total power consumption during the rebound period.

7 Conclusions

A fast demand response and power limiting control strategy is developed which achieves fast power reduction by shutting down some of the chillers directly. A novel control concept, cooling supply-based feedback control strategy, employing global and local cooling distributors based on adaptive utility function, is proposed to properly distribute the chilled water/air flow among different zones/spaces to maintain uniform thermal comfort sacrifice during DR events, instead of the commonly-used demand-based feedback control strategies.

Test results show that the proposed cooling supply-based feedback control strategy can facilitate the expected fast demand response and power limiting control strategies to achieve fast power reduction when receiving the demand response requests from smart grids. The proposed control strategy can effectively solve the disordered cooling distribution problem and achieve the uniform reduction profiles of the thermal comfort among different zones/spaces under limited cooling supply. In addition, the associated operation problems of using the conventional demand-based feedback control strategies, such as deficit flow and excessive speeding of secondary pumps and fans, are avoided. The increase of relative humidity is also alleviated during DR events. With the support of the proposed control strategy, the DR control strategy could achieve a significant power reduction, i.e., 24% of the power consumption with acceptable thermal comfort sacrifice. Furthermore, the use of the proposed strategy could significantly reduce the level of the power rebound after DR events and allow the air-conditioning systems to resume normal operation/control much quickly.

8 Acknowledgements

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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	i^{th} zone/space
out	outdoor

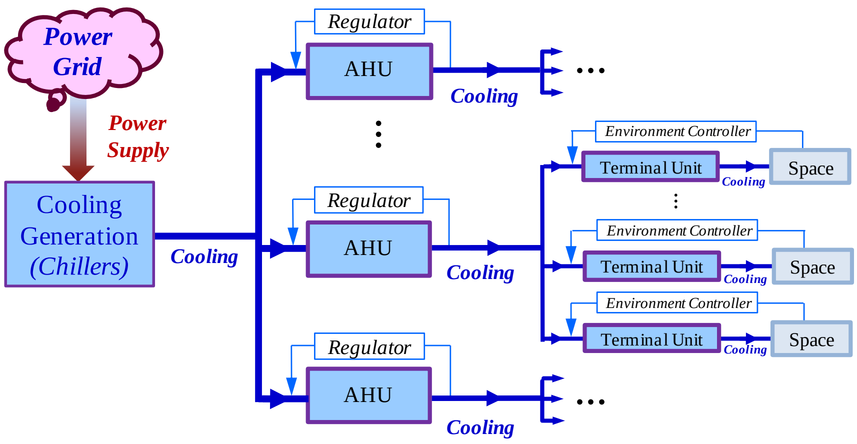

Fig.1. Basic principle of demand-based feedback control

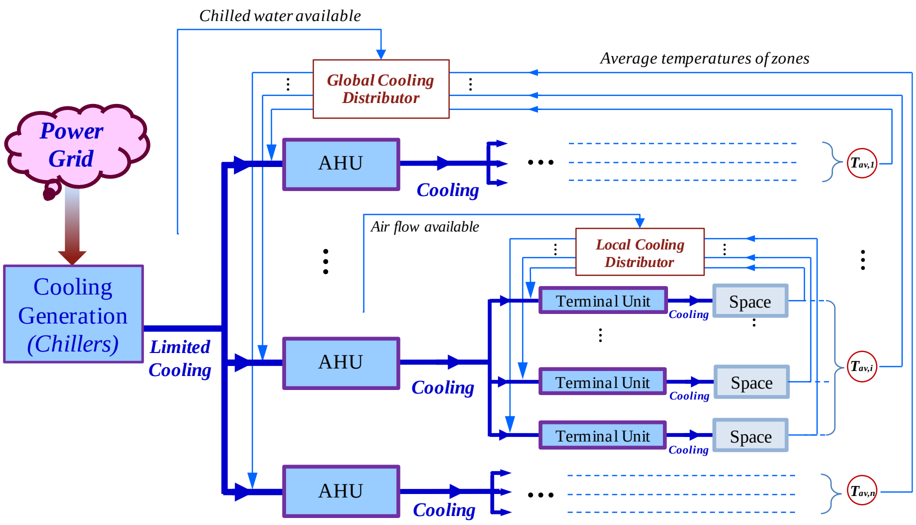

Fig.2 Basic principle of supply-based feedback control

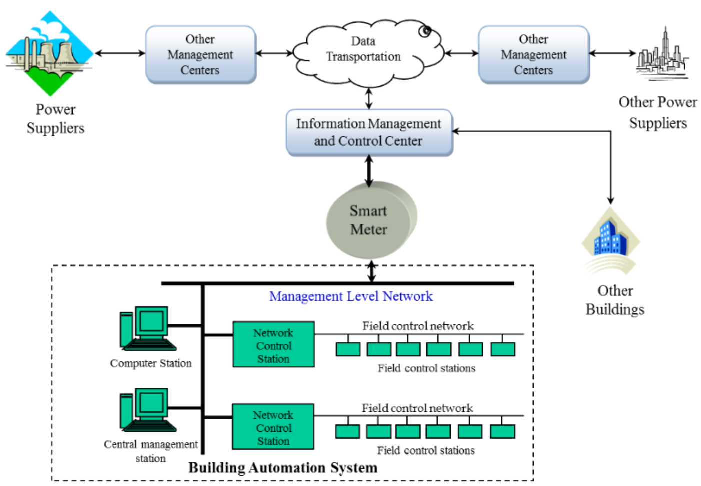

Fig.3 Implementation infrastructure of demand response control strategy

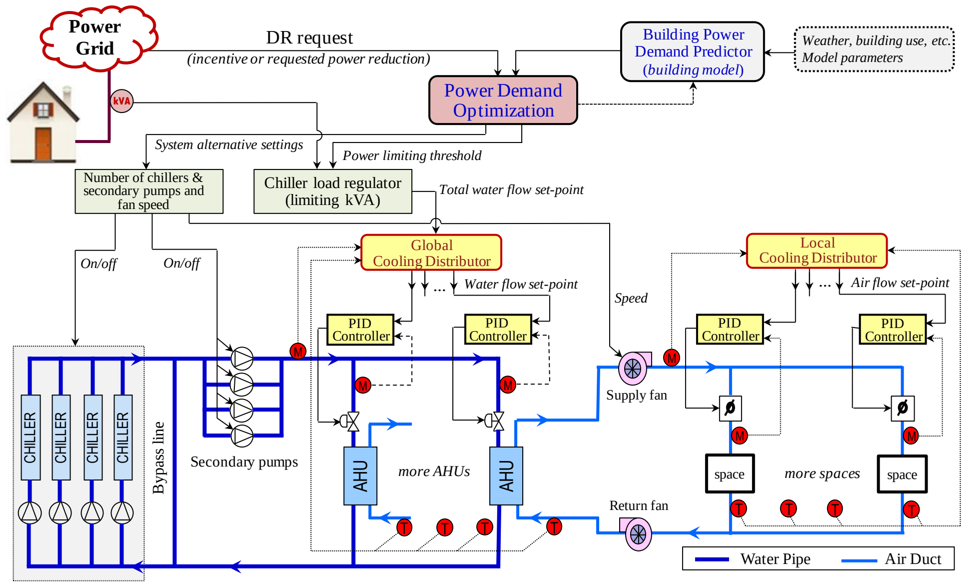

Fig.4 Schematic of fast demand response and power limiting control strategy for air-conditioning systems

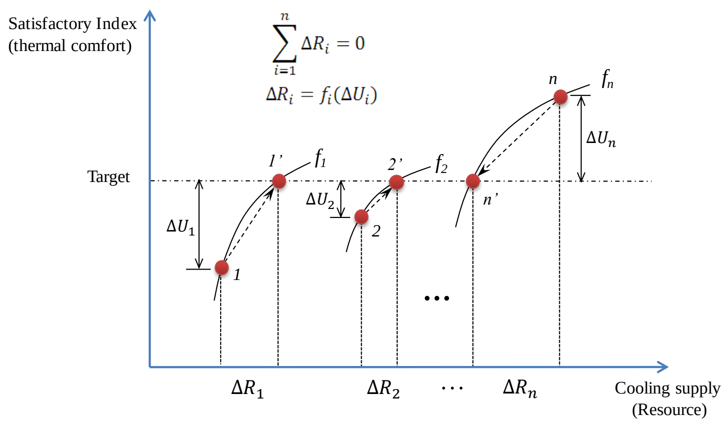

Fig.5 The basic working principle of cooling distributor

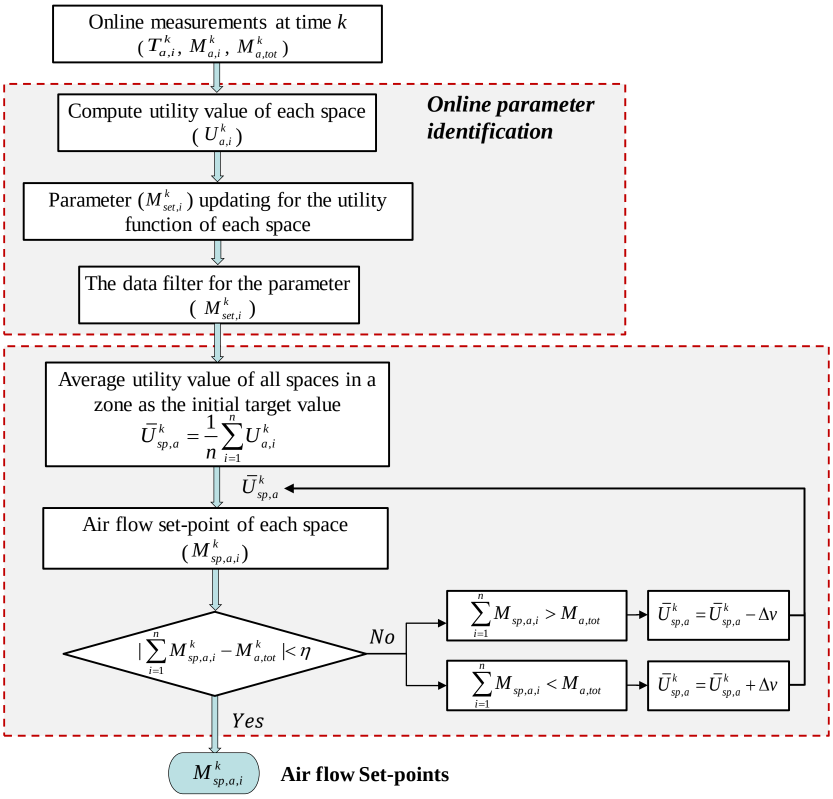

Fig.6 Flow chart of online air flow rate set-point reset scheme of local cooling distributor

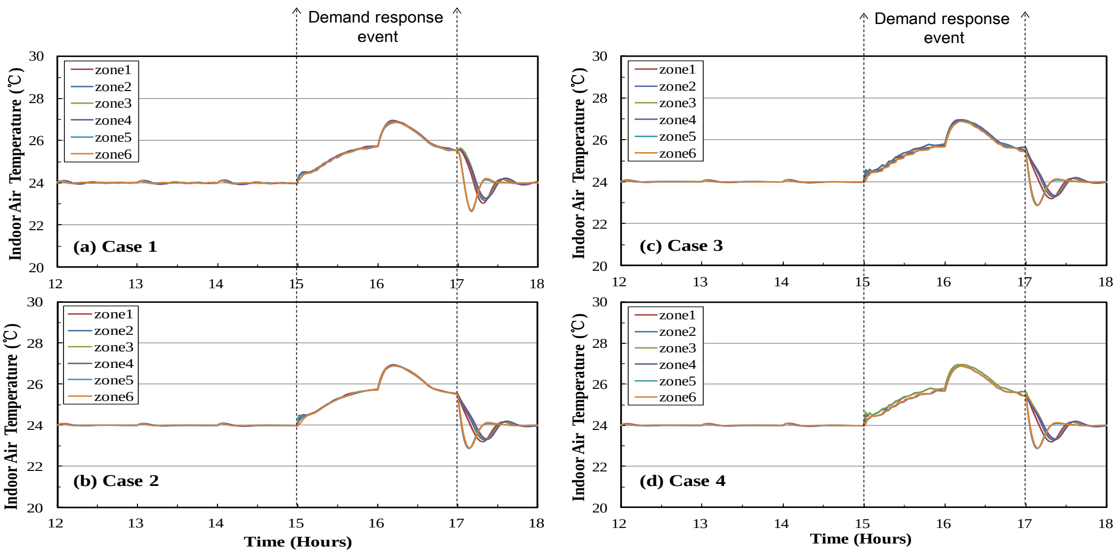

Fig.7 Indoor temperature profiles of four test cases using different values of a_i

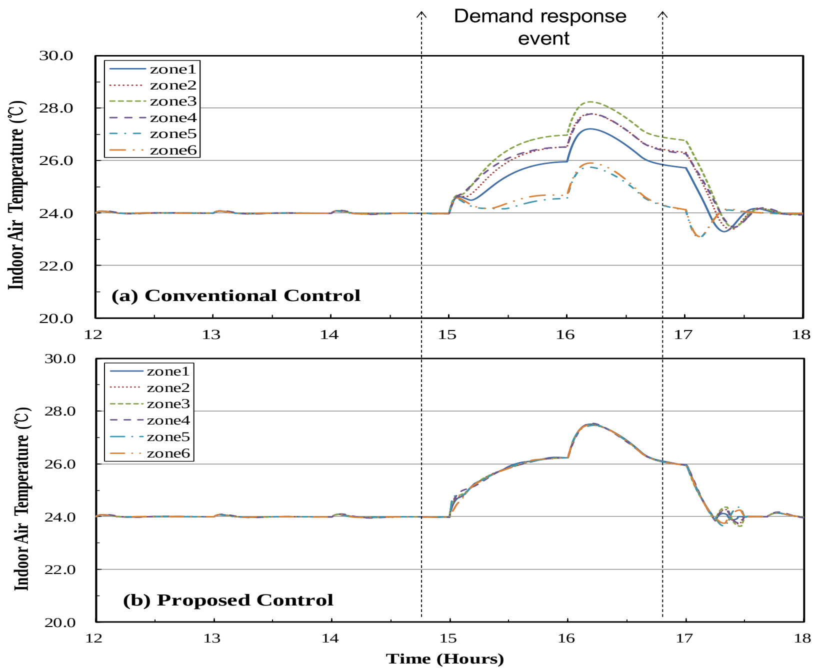

Fig.8 Indoor air temperature profiles of zones in DR tests using conventional and proposed strategies

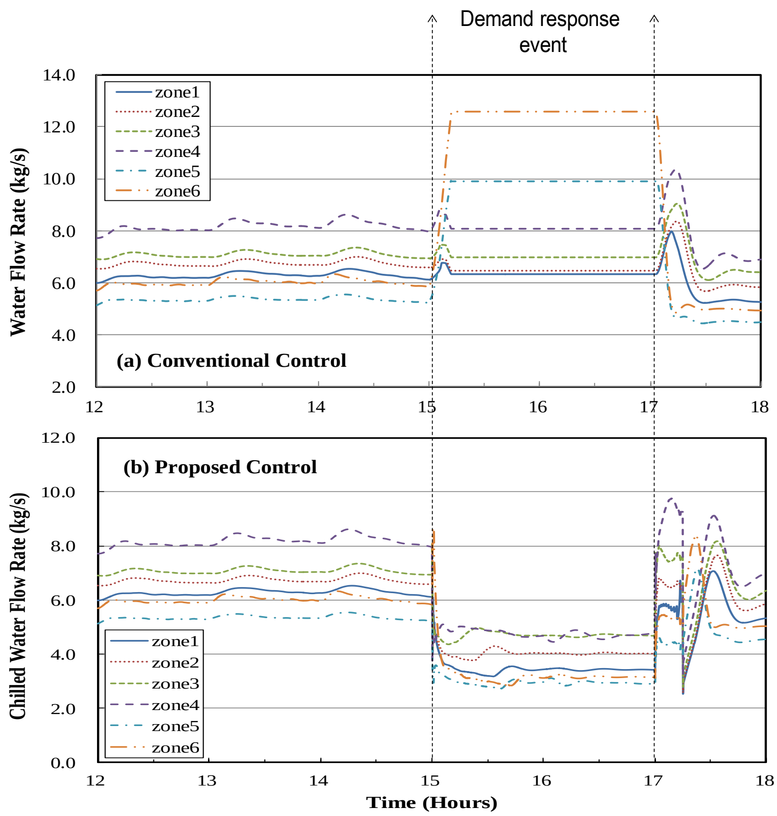

Fig.9 Chilled water flow profiles of zones in DR tests using conventional and proposed strategies

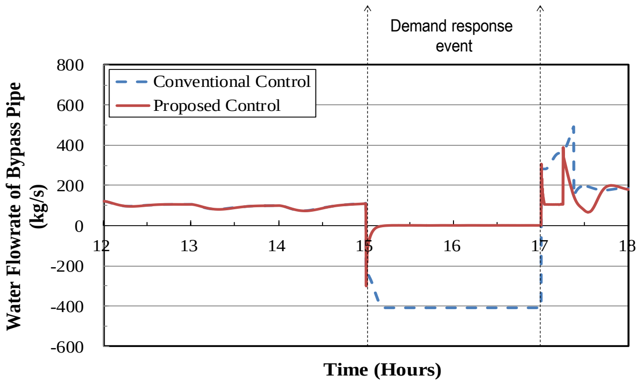

Fig.10 Water flow rates in by-pass line in DR tests using conventional and proposed strategies

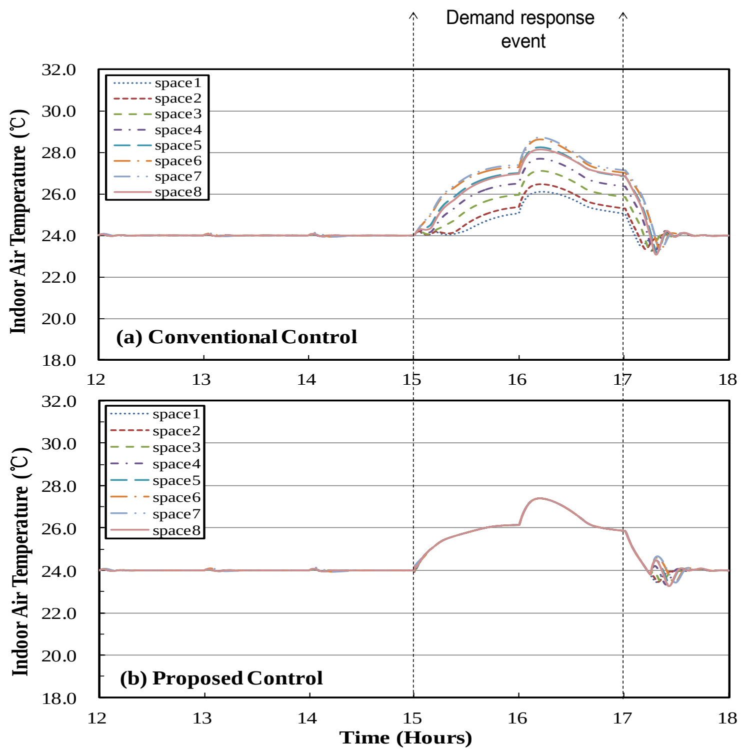

Fig.11 Indoor air temperature profiles of spaces in DR tests using conventional and proposed strategies

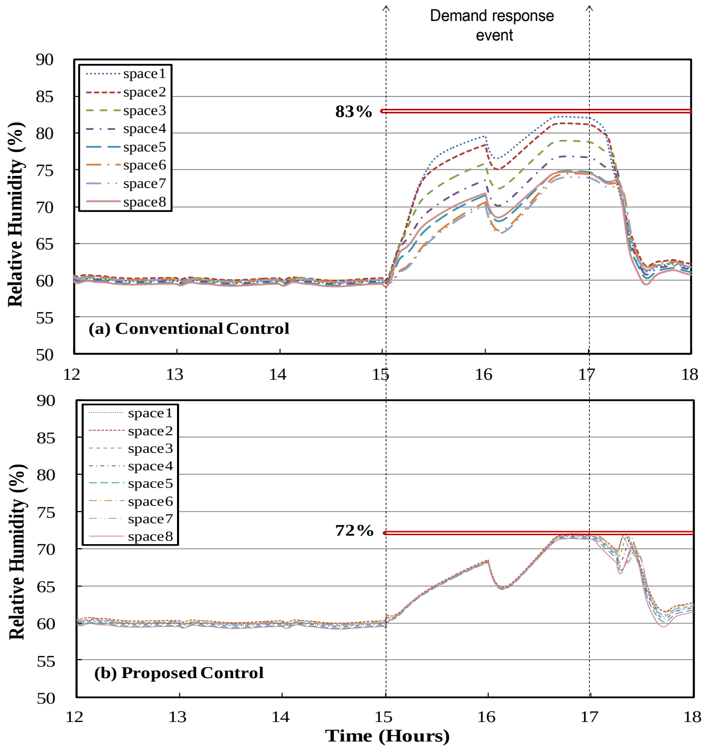

Fig.12 Indoor relative humidity profiles of spaces in DR tests using conventional and proposed strategies

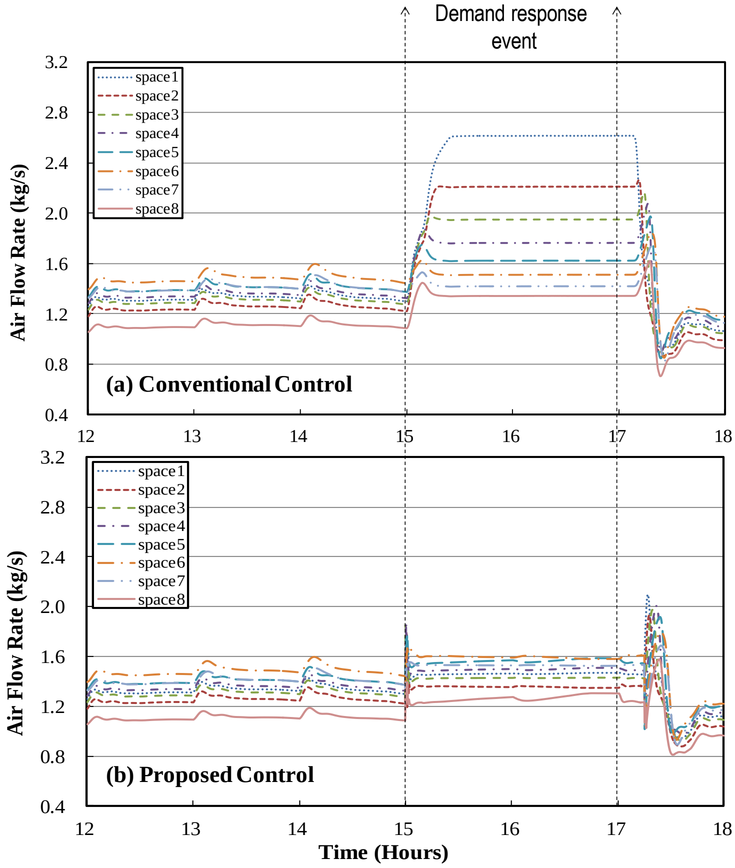

Fig.13 Air flow profiles of spaces in DR tests using conventional and proposed strategies

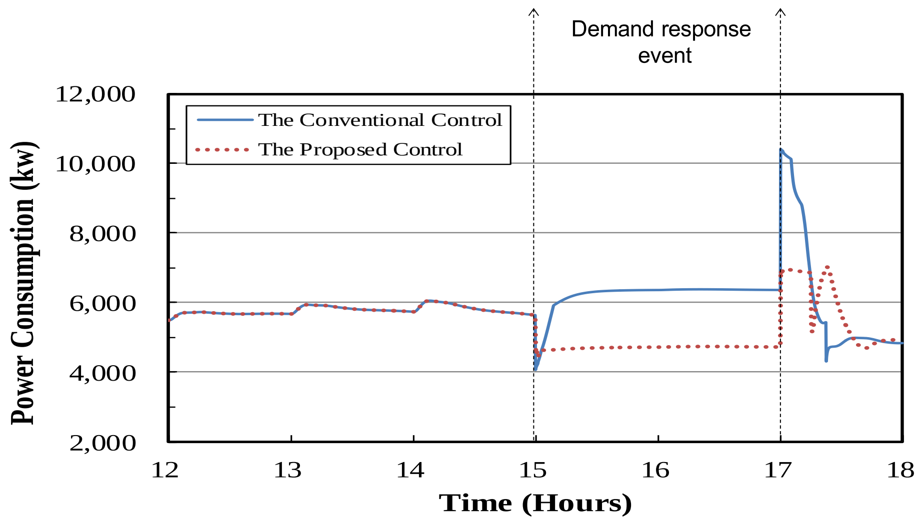

Fig.14 Power consumptions of chiller plant in DR tests using conventional and proposed strategies