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Reconfigurable supply-based feedback control for enhanced energy flexibility of air-conditioning systems facilitating grid-interactive buildings

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ABSTRACT

Air-conditioning systems have great potential to provide energy flexibility services to the power grids of high-renewable penetration, due to their high power consumption and inherent energy flexibilities. Direct load control by switching off some operating chillers is the simplest and effective means for air-conditioning systems in buildings to respond to urgent power reduction requests of power grids. However, the implementation of this approach in today's buildings, which widely adopt demand-based feedback controls, would result in serious problems including disordered cooling distribution and likely extra energy consumption. This study, therefore, proposes a reconfigurable control strategy to address these problems. This strategy consists of supply-based feedback control, incorporated with the conventional demand-based feedback control, a control loop reconfiguration scheme and a setpoint reset scheme, facilitating effective control under limited cooling supply and smooth transition between supply-based and demand-based feedback control modes. The proposed control strategy is deployed in a commonly-used digital controller to conduct hardware-in-the-loop control tests on an air-conditioning system involving six AHUs. Test results show that the reconfigurable control achieves commendable control performance. Proper chilled water distribution enables even thermal comfort control among the building zones during demand response and rebound periods. Temperature deviation of the building zones is controlled below 0.2 K most of the time. 11.6 % and 27 % of power demand reductions are achieved during demand response and rebound periods respectively, using the proposed reconfigurable control compared with that using conventional controls.

1. Introduction

The broader context of energy transition encompasses a global shift from fossil fuel-based systems of energy production and consumption to renewable energy sources, such as solar, wind, and hydroelectric power. This transition is driven by the urgent need to address climate change, reduce greenhouse gas emissions, and mitigate the environmental impacts associated with traditional energy sources. It involves a comprehensive transformation of the energy sector, including changes in technology, policy, and consumer behaviour. Carbon neutrality mission has become the foremost priority in the fight against climate change in the broader context of energy transition. To accomplish this mission, two fundamental strategies must be pursued: reducing energy consumption and increasing the penetration of renewable energy. However, the intermittent nature of renewable energy sources imposes great challenges to ensure real-time power balance, which could ultimately hinder efforts in increasing renewable energy penetration as shown in Fig. 1. Actually, such stress on the power grids can be reduced by making electricity loads flexible at the demand side. The heating, ventilation and air-conditioning (HVAC) systems of buildings present a distinctive prospect for cost-efficient demand management of buildings, as they are the primary power consumers especially in commercial buildings as they are responsible for over 1/3 of the electricity consumption in Hong Kong [1,2]. Enhancing energy flexibility of air-conditioning systems through smart control strategies to facilitate grid-interactive buildings is a critical aspect of the ongoing energy transition towards more sustainable, efficient, and resilient energy systems as shown in Fig. 1.

Many researchers have explored the control of air-conditioning systems for building-grid interaction. One of the most common control strategies is global zone temperature adjustment [3,4]. This strategy enables commercial buildings with zone-level temperature control to

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Nomenclature

Symbols

AHU	Air handling unit
PID	Proportional-Integral-Derivative
T_{sup}	Supply air temperature
T_{zone}	Indoor air temperature
K	Proportional gain
T_i	Integral time
PI	Temperature diversity indicator
a	Coefficient related to bypass pipe water flowrate

Subscripts

ave	Average
sp	Setpoint
i	Specific building zone
n	Number of building zones
by	Bypass pipe

modify their power usage by adjusting the space temperature setpoints on the whole-building level. It can be easily implemented by transmitting a signal from the central control stations to all the terminal space temperature control devices. The global zone temperature adjustment can alleviate the burden on associated air handling and cooling units of the air-conditioning systems. Many experimental studies revealed that this control strategy is effective for load shifting and load reduction. However, substantial time lag involved in processes of charging and discharging of the global zone temperature adjustment makes it difficult to achieve immediate power reduction (i.e., minutes) upon urgent requests from power grids [5–7]. Actually, building-grid response within a very short time holds exceptional importance for power grids in grid-level power balance management. The chiller plants represent the primary electricity demand in central air-conditioning systems [8,9]. Xue et al. [6] developed a fast chiller power demand response control strategy for buildings, and pointed out simply shutting down some essential operating chillers would result in disordered chilled water flow distribution and uneven indoor thermal comfort degradation. Tang et al. [10] introduced a power limiting control strategy that utilizes an adaptive utility function to update the chilled water flow setpoints of individual zones in real-time. The experimental results demonstrated that this proposed strategy could effectively address the issue of disordered water distribution and achieve a balanced sacrifice in thermal comfort across different building zones during the fast demand response period. Wang and Tang [5] also highlighted that conventional demand-based controls could lead to excessive speeding of chilled water pumps in situations with limited cooling supply, resulting in additional power consumption and a diminished effect of power limiting control. As a solution, they introduced the concept of supply-based feedback control and developed a cooling distributor that leverages an adaptive utility function. However, the implementation of such fast demand response controls in conventional building automation systems (BASs)

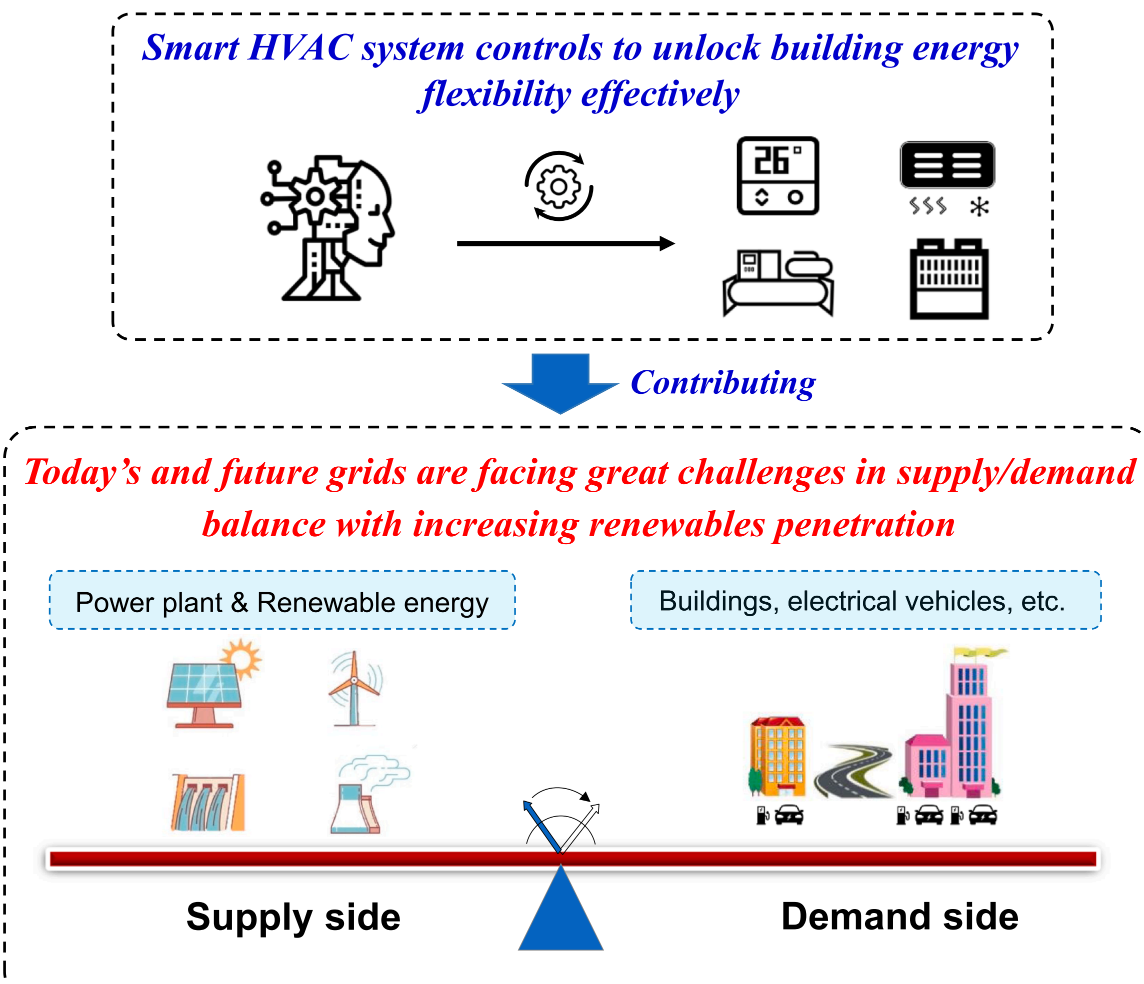


Fig. 1. Smart HVAC system control contributes to real-time power balance in the broader context of energy transition.

still remains to be difficult.

Modern building automation systems rely on digital controllers at field level, e.g., direct digital control (DDC) and programmable logic controller (PLC), for the centralized control and monitoring of HVAC systems in buildings [11]. Their implementation for a process control of HVAC systems involves the integration of a sensor, which continuously monitor the controlled variable, such as temperature, humidity, pressure and flow, and an actuator. According to the actual state of the controlled variable, the controller modulates process input via the actuator to maintain the controlled variable at desired set-point. Such feedback control is, in fact, by mean of modulating the use of the supplied resource based on the demand of the process. Demand-based feedback control is widely adopted in digital controllers for process controls of HVAC systems and many other industrial applications today [5,12]. The PID (Proportional-Integral-Derivative) control algorithm of various forms has been commonly used as the feedback control mechanism [13]. However, the conventional demand-based control is not suitable for fast demand response of building-grid interaction of [5–7]. It is because that such demand-based feedback control loops work well only under the provision of sufficient resource, such as the cooling supply provided by chillers is enough to fully meet the needs of terminal units. If the cooling supply is insufficient, the existing control systems would suffer from serious operational problems including serious imbalances in chilled water distribution among terminal units, over-speeding of pumps and fans. An author of this paper proposed smart control strategies to address these problems in his previous work [14,15]. However, the previous studies mainly focus on the distribution mechanism under limited supply, and the implementation issues of the control strategies are not considered. A strategy deployable in commonly-used digital controllers, such as DDCs, is urgently needed.

This study, therefore, proposes a reconfigurable supply-based feedback control for air-conditioning systems, which integrates supply-based feedback control, for demand limiting control under limited cooling supply, and demand-based feedback control under normal operation with sufficient cooling supply. In particular, this proposed strategy can be deployed conveniently in today's conventional digital controllers. The proposed strategy incorporates a control loop reconfiguration scheme and a setpoint reset scheme, facilitating effective demand limiting control and enabling smooth control transition between two control modes. The control loop reconfiguration scheme reconnects the controlled variable and resets the control parameters when the control mode switching from one to the other, and determines the proper time for mode switching. The commonly-used PID control function is adopted. The setpoint reset scheme determines the setpoint of the feedback loop in the demand limiting mode. The proposed control strategy is deployed in a typical commercial digital controller and tested by conducting hardware-in-the-loop control tests on a simulated air-conditioning system involving six AHUs. The novelty and contributions of this study are as follows:

- A reconfigurable supply-based feedback control for air-conditioning systems is proposed as a new norm for future buildings to facilitate the high renewable penetration of power system towards carbon neutrality.
- The proposed control strategy facilitates buildings the feature of fast demand response provision, enabling smooth control transition between normal mode and demand limiting mode for proper cooling distribution.
- Hardware-in-the-loop control tests are conducted, and the results validate that the proposed control strategy can be conveniently deployed in conventional digital controllers of existing building automation systems.

2. Reconfigurable control strategy

2.1. Outline of reconfigurable control

Fig. 2 depicts the block diagram of the reconfigurable feedback control. Basic mechanism of the proposed reconfigurable control is to adjust or reconfigure feedback control loop online to match different needs or objectives of controls under demand limiting with limited resource/supply and under normal situation with sufficient supply. The strategy can be deployed in the commonly-used digital controllers of building automation systems, facilitating the possibility and convenience of its wide implementation. The control loop reconfiguration scheme reconnects the controlled variable when the control mode switching from one to another. In the implementation case of this study, Process 1 refers to the AHU, while Process 2 refers to the building zone. As the dynamics of the controlled processes controlled by the same digital controller in two different control modes is different, the parameters of the feedback controller are reset to enable smooth transition in two different control modes. The setpoint reset scheme determines the setpoint of the feedback controller. In the system concerned, the controlled variables are the AHU valve openings. In normal operating mode (demand-based feedback control), the operational objective is maintaining a specific supply air temperature. When the fast demand response is conducted, specific chillers are shut down immediately. The control objective is to achieve proper cooling distribution. The detailed working mechanism of the control loop reconfiguration scheme and the setpoint reset scheme is elaborated in the following section (i.e., Section 2.2).

2.2. Reconfigurable feedback control strategy

2.2.1. Basic feedback control law

Eq. (1) shows the basic control law of a basic PID controller [13]. Where, $u(t)$ is the control signal and $e(t)$ is the error signal at time t. The PID controller continuously calculates this control signal based on the error signal and the proportional gain K, integral time T_i and derivative time T_d, to control the controlled process output at the desired setpoint. y is the controlled variable and y_{sp} is the setpoint for the controlled variable. The PID control law consists of three terms as shown in Eq. (1). The proportional term provides a direct relationship between the error and the control output. The integral term integrates the error over time, which helps to eliminate steady-state errors. The derivative term anticipates future errors by measuring the change rate of the error.

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d(\tau) + T_d\frac{de(t)}{dt}\right) \tag{1}$$

$$e(t) = y_{sp}(t) - y(t) \tag{2}$$

In the normal operating mode (i.e., demand-based control), the AHU valve position is adjusted to maintain a specific supply air temperature. In this situation, the controlled variable is the supply air temperature. A combination of proportional and integral control (i.e., PI control) is often used in practical applications.

2.2.2. Supply-based feedback control and control loop reconfiguration scheme

Fig. 3 illustrates the schematic of the air-conditioning system concerned, the supply-based feedback control and the control loop reconfiguration scheme. In both control modes, the controller adopts the feedback control law as described in Section 2.2.1. In normal control mode (demand-based feedback control), the controlled variable (y_i) of an AHU control is the AHU supply air temperature as shown in Eq. (3). Its control setpoint is determined according to the needs of sensible and latent cooling demands, typically given as a fixed value such as 15 °C, which might be optimized and reset according to the change of load

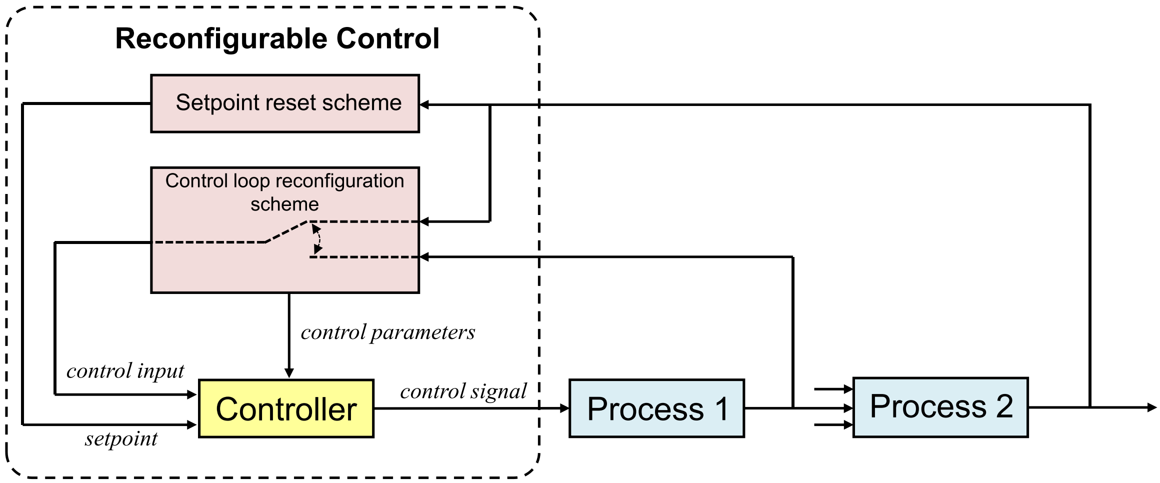


Fig. 2. Block diagram of the feedback loop reconfiguration.

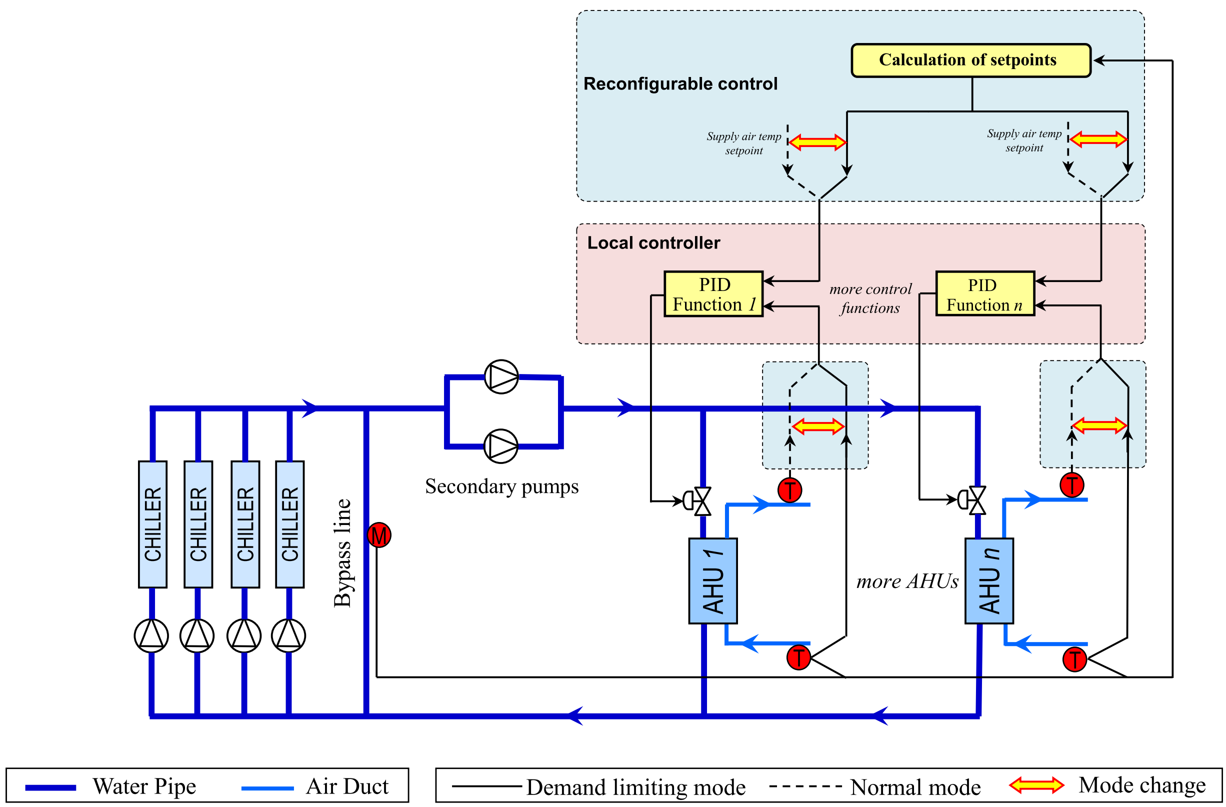


Fig. 3. Schematic of the central air-conditioning system and the architecture of supply-based feedback control.

condition. When the demand limiting mode is activated, some operating chillers will be switched off immediately and only limited (cooling) supply is available. In such condition, the cooling distribution among AHUs would be disordered if the same demand-based feedback control is used. To solve this problem, a supply-based feedback control is introduced. In supply-based feedback control mode, the controlled variable (y_i) of an AHU control is indoor air temperature in the corresponding zone represented by the returned air temperature from the zone, as shown in Eq. (4). In order to maintain a uniform temperature among different zones, which is definite objective of adopting supply-based feedback control, a common control setpoint is used for the AHU control loops of all zones. As the cooling supply is insufficient to maintain a constant or preferable comfort temperature, the control setpoint in this mode is adjusted adaptively as elaborated in Section 2.2.3.

$$y_i(t) = T_{sup,i}(t) \tag{3}$$

$$y_i(t) = T_{zone,i}(t) \tag{4}$$

2.2.3. *Setpoint reset scheme*

The setpoint for the AHU return air temperature control loops is reset according to Eq. (5), which consists of two terms. The first term is the average return air temperature. It aims to achieve uniform temperature among the zones. The second term is introduced as an adjustment term to consider the deficit water flow rate (i.e., M_{by}) in the bypass pipe, in order to eliminate the deficit flow in the demand limiting mode.

$$y_{sp}(t) = \frac{\sum_{i=1}^{n} T_{zone,i}(t)}{n} - a \cdot M_{by} \tag{5}$$

where, the coefficient a is adjustable to achieve better control performance for demand response. Fig. 4 shows the process of control mode switching (i.e., transition from normal operation to demand response, and then reverts to normal operation). There are two transition processes (i.e., Switching 1 and Switching 2 in Fig. 4) in the proposed control strategy switching from one mode to the other. Switching 1 denotes the transition from normal operation to demand response. At this moment, the control loop reconfiguration scheme is activated to enable demand limiting and proper distribution of limited cooling. Switching 2 denotes the transition from demand limiting mode back to normal mode, while the air-conditioning system ends the task of demand limiting. The chiller plant can now provide sufficient cooling supply as demanded to restore the indoor air temperature of the zones to their comfort setpoints. To ensure better control performance during the two switching moments and throughout the demand response and rebound periods, the parameter scheduling of coefficient a is implemented. The details for scheduling the parameter, i.e., coefficient a, are illustrated in Fig. 5 and elaborated below.

2.2.3.1. Parameter setting at switching 1. At the switching moment from normal operation to demand response (i.e., Switching 1), the control loop reconfiguration scheme is activated to modify the inputs of the PID functions, as explained in Section 2.2.2. In the normal mode, the temperature in each building zone is regulated to designated comfort setpoint of 24 °C, resulting in minimal deviation among zones. In order to eliminate the deficit flow as soon as possible, the initial value of coefficient a in Eq. (5) is set relatively high (i.e., a_0 in Fig. 5).

2.2.3.2. Parameter setting during demand limiting mode. During the transition period following the switching 1, the purpose of setting coefficient a is to mitigate the deficit flow problem and prevent control instability. In order to achieve this, a decreasing parameter schedule is implemented for coefficient a starting from the initiation of the demand response event (i.e., t_A) for a short duration (from t_A to t_B). The parameter schedule is set by Eq. (6), where a_0 is the initial setting and r determines decreasing speed. This approach ensures a gradual adjustment of coefficient a over the transition period following Switching 1, contributing to a controlled and stable system response during the demand response period.

$$a(t) = a_0 e^{-rt} \tag{6}$$

2.2.3.3. Parameter setting at switching 2. At the switching moment from demand limiting mode to normal mode (i.e., Switching 2), the control objective is to properly distribute the available cooling supply in order to restore the temperature of these building zones to comfort setpoints. In this situation, coefficient a is set to 0 since the deficit flow problem is no longer a concern due to the sufficient cooling supply. However, considering the need to rapidly cool down the zones, the AHU valve openings should be relatively larger. Therefore, the set of a back to 0 is delayed for a short period (i.e., from t_C to t_D in Fig. 5) to facilitate a quicker cooling response.

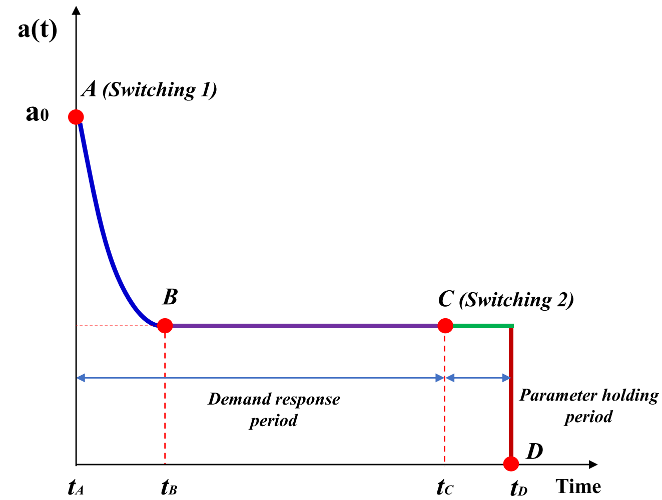


Fig. 5. Parameter scheduling of coefficient a.

2.2.4. Control performance indicators

To assess the control performance of cooling distribution, a temperature diversity indicator, denoted as *PI*, is proposed in Eq. (7). In this equation, PI_i represents the performance indicator for a specific zone i in the building. Where, n denotes the total number of zones. The function of this indicator is to quantify the temperature diversity among the zones, aiming for a lower value to achieve the desired control objective of proper cooling distribution. Additionally, accumulated valve travel distance (AVTD) [14] is utilized for quantifying the control stability of the AHU valves. AVTD is calculated using Eq. (8). Where, Δu_t denotes the valve position modification during each sampling period t. I denotes overall number of sampling periods within demand limiting mode.

$$PI_i(t) = \left| T_{zone,i}(t) - \frac{\sum_{i=1}^{n} T_{zone,i}(t)}{n} \right| \tag{7}$$

$$AVTD = \sum_{t=1}^{I} \Delta u_t \tag{8}$$

3. Arrangement of validation tests

3.1. Test platform

To ensure the practical applicability concerning actual deployment and operation of the proposed control strategy, we have developed a hardware-in-the-loop experimental platform to closely simulate real-world conditions, as illustrated in Fig. 6. This platform incorporates a physical programmable logic controller (PLC) as the feedback controller for regulating the valve openings of the AHUs within the central air-conditioning system. Specifically, we have employed a SIMATIC S7–1200 controller from Siemens as the hardware component of our

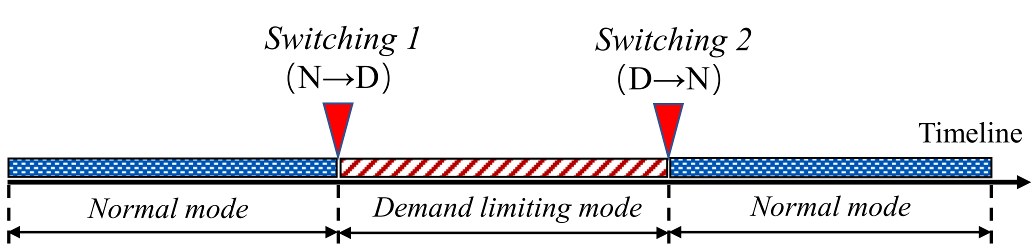


Fig. 4. Process of the control mode switching.

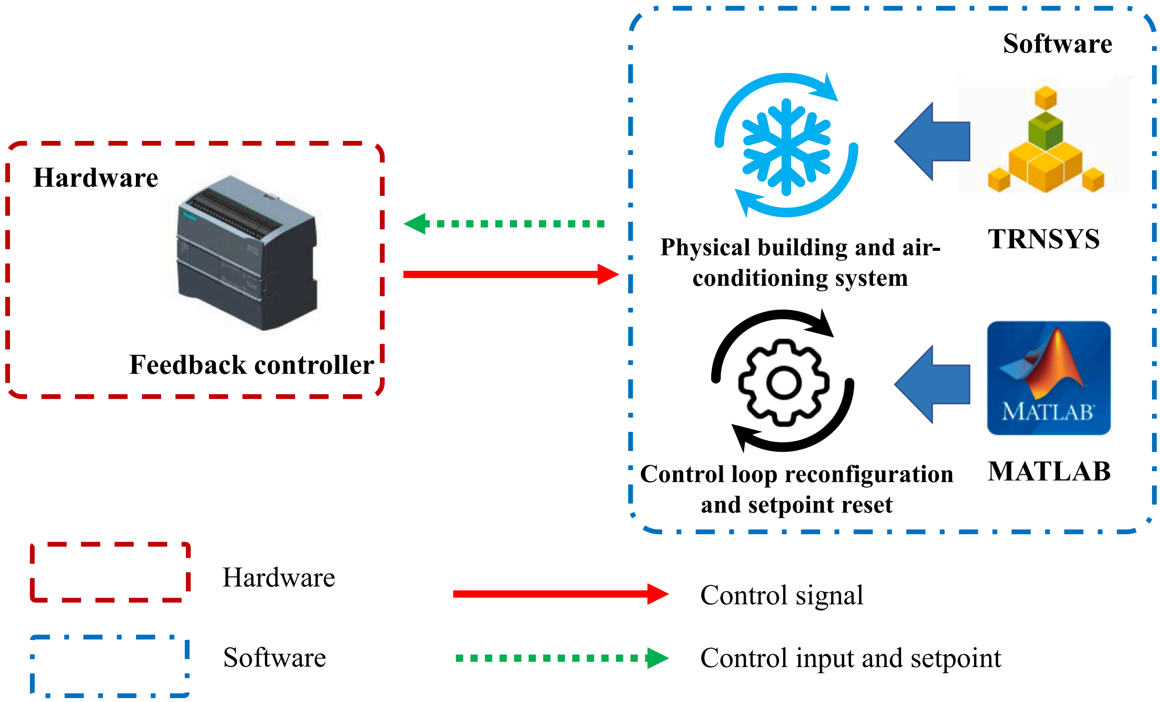


Fig. 6. Hardware-in-the-loop test platform.

platform. To accurately emulate the behavior of building thermal dynamics and various HVAC components (such as chillers, AHUs, hydraulic network, etc.), we have constructed detailed physical models in TRNSYS [16]. The simulated building represents a high-rise commercial structure located in Hong Kong, taking into account relevant studies [12,14,15]. The software side is capable of managing dynamic processes associated with heat transfer, hydraulic properties, water balance, and energy conservation within the physical building and air-conditioning system [17,18].

Fig. 3 illustrates the central air-conditioning system employed. It is a standard primary-secondary variable flow system. The chilled water system comprises four uniform-capacity chillers duty chillers, each with a nominal capacity of 4080 kW. The primary water pumps maintain a constant speed, each delivering a designated flowrate of 172.8 L/s. In the secondary chilled water circuit, two pumps with adjustable speeds are installed. These pumps allow for flexibility and control over the flowrate. The AHUs are in charge of delivering cooling to the various building zones. In this study, six typical building zones, each covering 1600 m^2, are simulated to represent the entire air-side system of the building after multiplying their loads by a factor of 15. An AHU is installed to supply cool air to each zone. The building operates during office hours from 8:00 to 18:00. Throughout this period, all six zones maintain an indoor air temperature setpoint of 24 °C in normal operation.

3.2. Test arrangement

As shown in Fig. 6, the hardware-in-the-loop platform establishes a connection between the physical hardware and the software component using the Modbus protocol. The hardware-in-the-loop test platform consists of a programmable logic controller (PLC) on the hardware side to deploy the reconfigurable control strategy, and software components including TRNSYS for building and air-conditioning system simulation and MATLAB. MATLAB is adopted for implementing supervisory schemes for the reconfigurable control, i.e., control loop reconfiguration and setpoint reset, which will typically be deployed in BAS network stations. The physical PLC receives control input and setpoint from the simulated virtual part of the platform. It then sends control signal, specifically the AHU valve openings, back to relevant devices in the simulated virtual part of the platform. The half-day's (12:00–24:00) real-time validation tests are conducted using the weather data on a typical summer day (July 23rd) in Hong Kong, while two-hour demand response event 14:00 to 16:00 is included. During this demand response event, two out of four operating chillers are switched off, while the two remaining chillers continue to operate. Comparative studies are performed to evaluate the performance of the control strategies.

Strategy I - Conventional control strategy. In this approach, conventional control is maintained. The AHU valve position is adjusted to maintain the same supply air temperature.

Strategy II - Reconfigurable control strategy without parameter scheduling. During the normal operating mode, the field digital controller adopts the conventional feedback control for AHU valve modulation. The feedback control loops for the six AHUs are set with the same proportional gain (K) of −0.005 and integral time (T_i) of 50 s. The coefficient a in Eq. (4) is fixed at 0.05 throughout the demand response event.

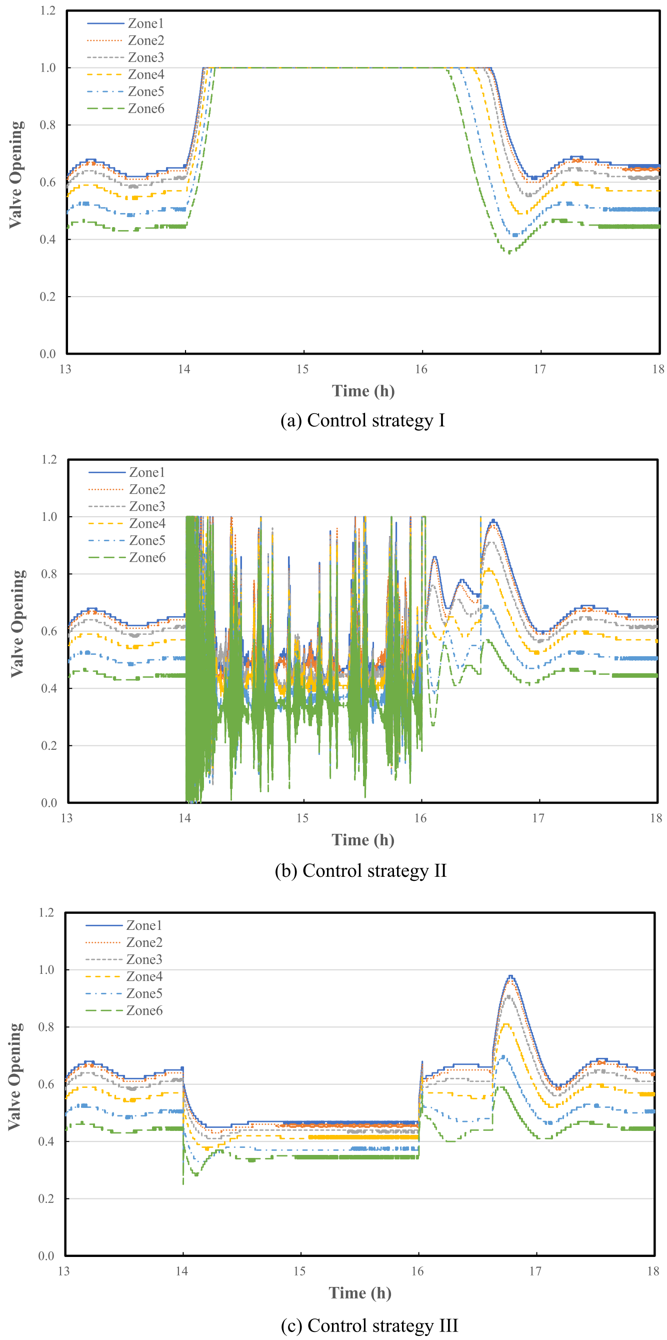
Strategy III - Reconfigurable control strategy with parameter scheduling. This approach involves complete reconfigurable control as described in Section 2. The parameter scheduling method is employed to adjust the coefficient a (refer to Eq. (4)) according to the schedule outlined in Section 2.2.3. The duration of the decreasing parameter schedule (t_B - t_A) for coefficient a is set to 60 s, the duration for holding the value of coefficient a is set to 100 s (i.e., t_C - t_D), and the decreasing rate r in Eq. (8) is set to 0.05.

4. Test results

4.1. Control performance

4.1.1. Valve opening

Fig. 7 shows the valve opening profiles of the building zones under three different control strategies. I Using the control strategy I as shown in Fig. 7(a), the valve openings are increased to maintain the supply air temperature setpoints. All AHU valves reach their maximum opening positions within approximately 15 min and remain fully open



(a) Control strategy I

(b) Control strategy II

(c) Control strategy III

Fig. 7. Valve opening profiles using different control strategies.

throughout the two-hour demand response event. Furthermore, it is important to note that even after the demand response event ends, all valves continue to remain fully open for over 10 min. It indicates that when shutting down operating chillers for demand limiting, the cooling supply from the remaining chillers is insufficient to meet the cooling demand of terminal units.

Fig. 7(b) shows the valve opening profiles when using control strategy II. These test results indicate that, using fixed control parameters, strong oscillations occur in the valve opening control. The occurrence of such oscillations can be attributed to an excessive and fixed setting of coefficient *a*. Besides, the oscillations can cause mechanical wear and fatigue on these components, potentially reducing their lifespan and overall reliability.

On the contrary, the problem of control instability can be avoided under the control strategy III as shown in Fig. 7(c). The proactive adjustment helps alleviate the deficit flow problem very quickly. Moreover, the oscillation problem observed in control strategy II is effectively avoided through scheduling coefficient *a*. Once the demand response event ends at 16:00, the valve openings are generally adjusted to increase for a short period of 2 min. This adjustment ensures that more chilled water is provided to cool down the building zones effectively. Subsequently, the supply-based feedback control continues to adjust the valve openings for proper cooling distribution during the cooling down period. Fig. 8 presents a comparison between the accumulated valve travel distances (AVTD) of control strategy II and control strategy III. The results show an average reduction of AVTD by 98 % when replacing control strategy II by control strategy III. This reduction demonstrates the effectiveness of the proposed reconfigurable control strategy in achieving better control stability during fast demand response events.

4.1.2. Chilled water distribution

Fig. 9 shows the chilled water flowrates of different zones under different scenarios. Fig. 9(a) presents that the water flowrate distribution among zones is disordered using conventional control. The chilled water flowrates of all zones begin to increase in correlation with the upward trend of the valve openings at 14:00. During this event, six AHU valves are controlled to be fully open. However, due to variations in hydraulic resistance among the AHUs, the distribution of chilled water becomes uneven. This disorderly distribution arises because the chilled water loop with lower resistance (e.g., AHU 6) receives a much larger share of chilled water distribution. Conversely, the chilled water loop at a more distant site (e.g., AHU 1) receives less chilled water, even when its valve has been already fully opened. The problem of uneven water distribution persists even after 16:00, during the rebound period. Fig. 9 (b) presents the chilled water flowrate profiles using control strategy II. There are strong oscillations in valve opening control, resulting in oscillations in chilled water flowrate distribution. This instability in the system control leads to a decrease in overall performance of the controlled process. However, the problem is eliminated in the test using control strategy III as shown in Fig. 9(c). As discussed in Section 3.2, the proper adjustments in valve openings lead to a more appropriate distribution of chilled water.

4.1.3. Deficit flow in bypass pipe

Fig. 10 shows the profiles of water flowrates in the bypass pipe using different strategies. There is a severe deficit flow problem from 14:00 to 16:00 when using control strategy I. Such deficit flow leads to a reduction in the temperature difference of the chilled water supplied to the building zones, resulting in decreased cooling effectiveness. Furthermore, the inability to meet the cooling demand of the building zones causes the secondary chilled water pumps to operate at full load.

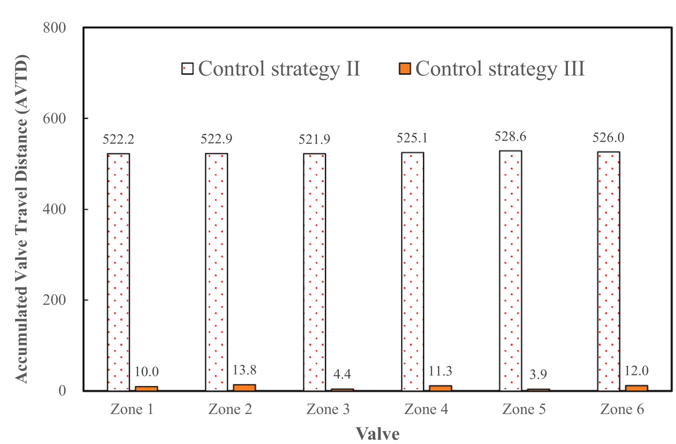
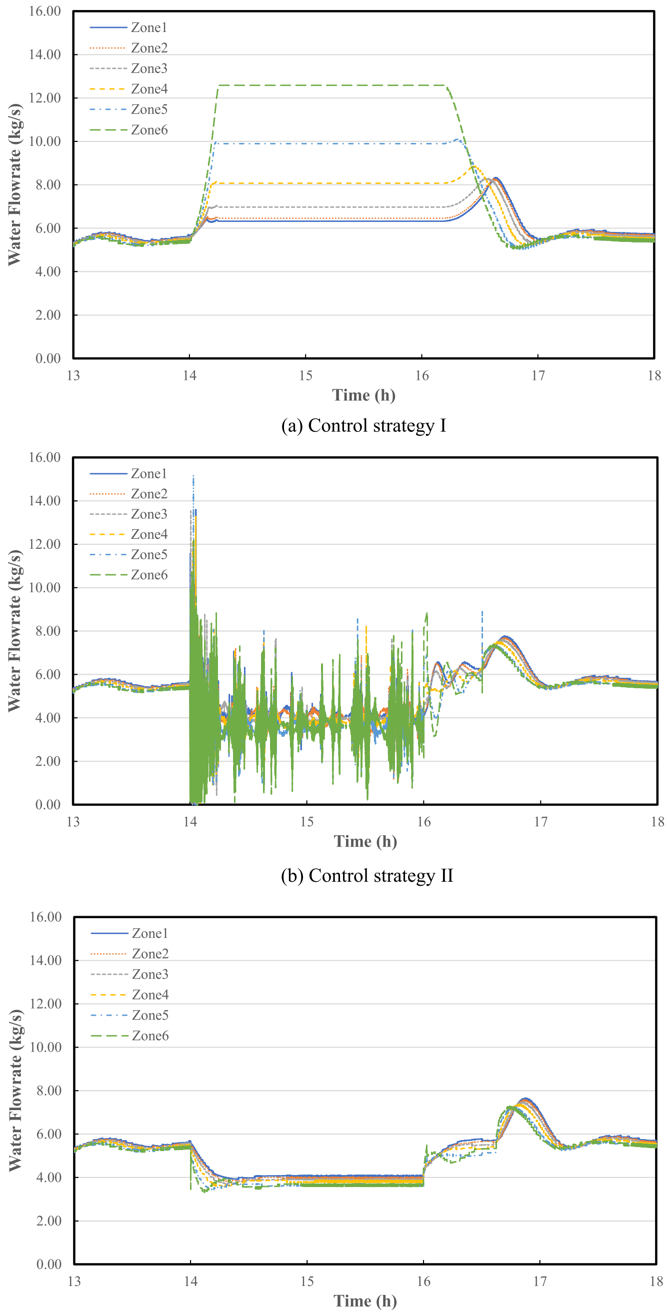


Fig. 8. Comparation of accumulated valve travel distance between control strategy II and control strategy III.



(a) Control strategy I

(b) Control strategy II

(c) Control strategy III

Fig. 9. Chiller water flowrate profiles under different control strategies.

This, in turn, increases energy consumption and adds to the overall energy inefficiency of the system.

The bypass pipe water flowrate profile using control strategy II demonstrates strong oscillations during the demand limiting mode. This phenomenon is a result of the lack of a proper parameter adjustment of coefficient a, which leads to oscillations in the bypass pipe water flowrate. On the other hand, when using control strategy III, the phenomenon of deficit flow gradually diminishes from 14:00. It takes approximately 12 min to eliminate the deficit flow. With this proposed supply-based feedback control, the deficit flow is effectively avoided throughout the demand response event, and no oscillations occur in the bypass pipe water flowrate.

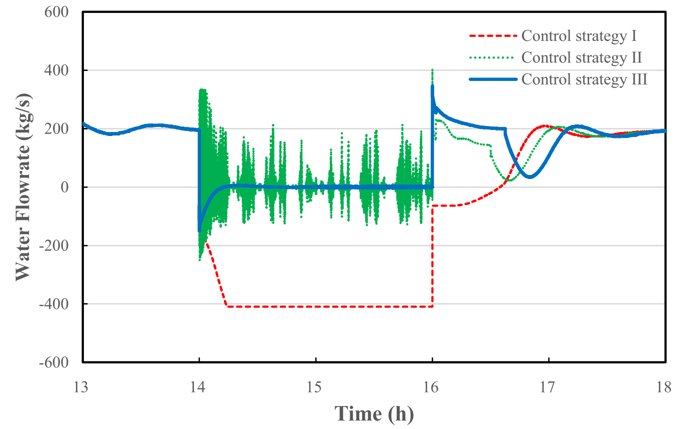
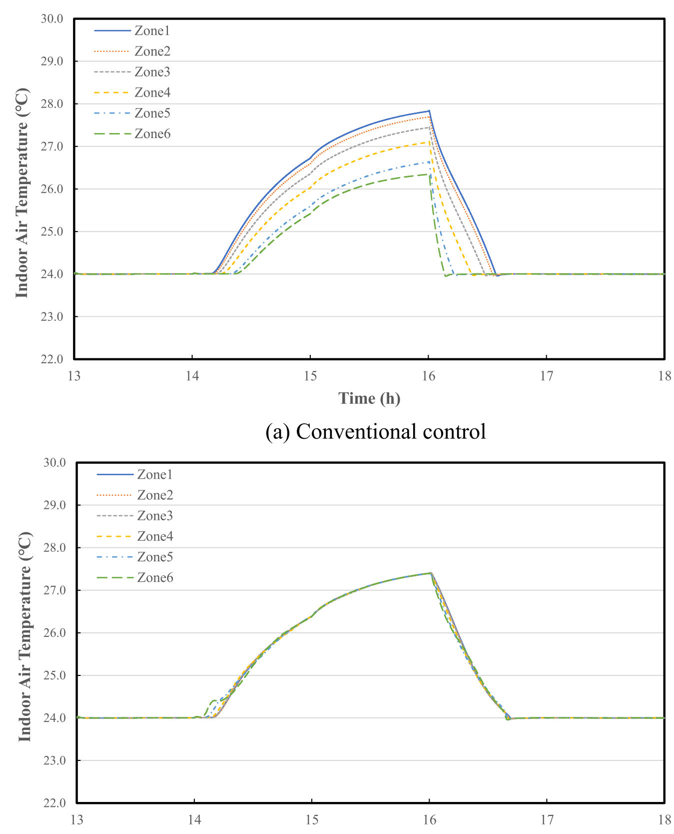


Fig. 10. Bypass pipe water flowrate profiles using different control strategies.

4.2. Environmental and energy performance

The previous section has highlighted the effectiveness of the proposed control in adjusting AHU valve openings to ensure proper chilled water distribution during fast demand response events. Test results confirm the importance of parameter scheduling in order to avoid control oscillations and achieve improved control performance. This section focuses on the comparison of the environmental and energy performance between conventional control (Control strategy I) and the reconfigurable control (Control strategy III).



(a) Conventional control

(b) Reconfigurable control

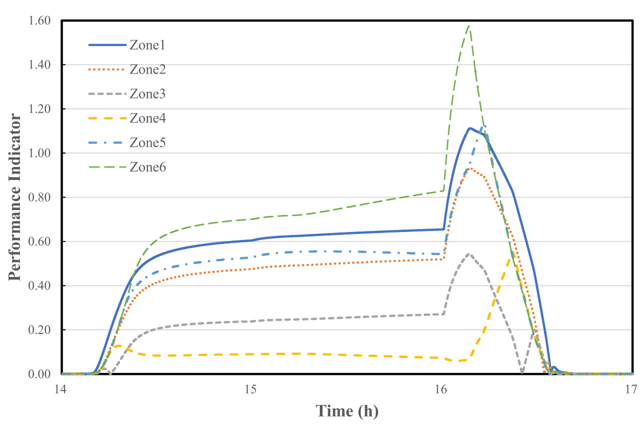
Fig. 11. Comparation of indoor air temperature profiles using conventional control and reconfigurable control.

4.2.1. Indoor air temperature

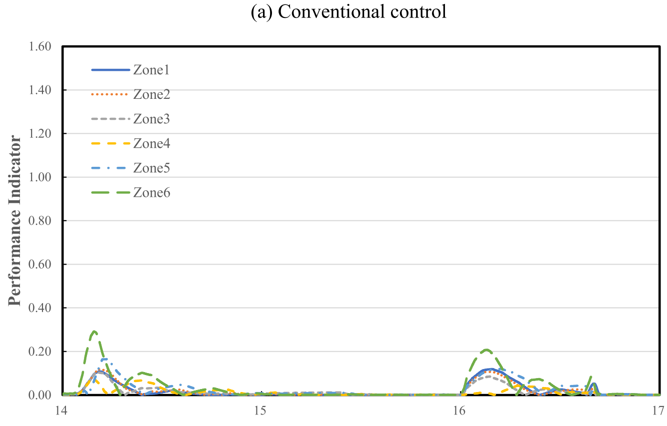
Fig. 11 presents a comparison between the indoor air temperature profiles of the conventional control and reconfigurable control. When using the conventional control, there are significant differences in temperature sacrifices among all building zones. In addition, the cooling down speeds also deviate significantly among the zones during the rebound period. Fig. 12(a) presents the temperature diversity performance indicators using conventional control. The test results demonstrate for the majority of the zones, their temperature diversity indicators remain above 0.2 K for most of the time, indicating imbalanced thermal comfort sacrifices. This imbalance arises from improper chilled water distribution, as discussed in Section 4.1.2. However, when the proposed reconfigurable control is implemented, the problem of imbalanced thermal comfort sacrifices can be effectively addressed, as shown in Fig. 11(b). The diversity indicators of all six zones can be controlled within 0.2 K for most of the time.

4.2.2. Energy consumption

Fig. 13 shows the comparison between the secondary pump energy consumptions of conventional control and reconfigurable control. The energy consumption of the secondary pumps begins to increase at 14:00 due to the growing valve openings using the conventional control. The maximum energy consumption reaches 360 kW from 14:00 to 16:00. In contrast, the supply-based feedback control with proper valve opening adjustments significantly reduces the energy consumption of the secondary pumps. The maximum energy saving during the demand response event reaches 287 kW, which is crucial in achieving the desired effects of demand response. Fig. 14 provides a comparison between air-conditioning system energy consumptions using conventional control and reconfigurable control respectively. In demand limiting mode, the power reduction of the chilled water system is 561.5 kWh, corresponding to a further reduction of 11.6 %, when replacing the conventional feedback control by the supply-based feedback control. In addition, the power rebound is also reduced by 532 kW, corresponding to 27 % of power rebound when using the conventional control.



(a) Conventional control



(b) Reconfigurable control

Fig. 12. Comparation of temperature diversity performance indicators using conventional control and reconfigurable control.

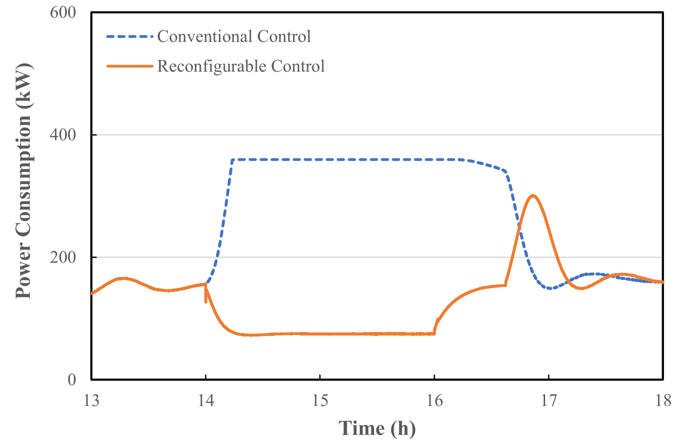


Fig. 13. Comparation of secondary pumps energy consumption using conventional control and reconfigurable control.

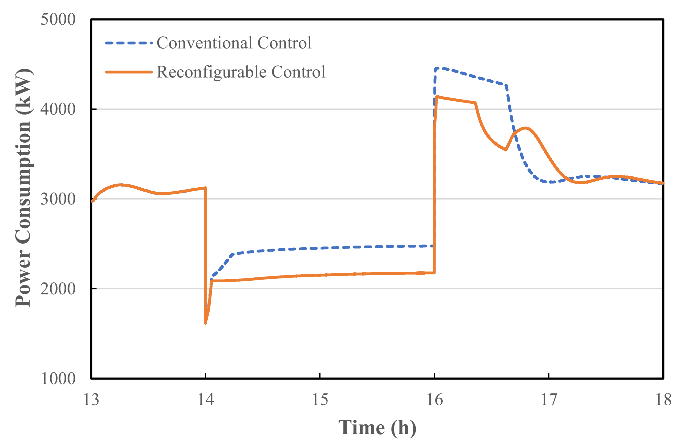


Fig. 14. Comparation of air-conditioning system consumption using conventional control and reconfigurable control.

5. Conclusions

Air-conditioning systems have the potential to provide valuable energy flexibility services, especially when faced with urgent power reduction requests from power grids. Adopting supply-based feedback controls and integrating them with demand-based feedback controls, as a reconfigurable control strategy, are proposed and recommended for air-conditioning systems to facilitate buildings the feature of fast demand response provision. Reconfigurable control strategy integrating supply-based feedback controls, for demand response and demand limiting events, and demand-based feedback controls, for normal situation with sufficient cooling supply, should be the new norm for future buildings to facilitate the high renewable penetration of power system towards carbon neutrality. Based on the results of validation tests, the following major conclusions can be made:

- The conventional building automation systems adopting conventional feedback control face challenges in distributing cooling supply effectively during fast demand response while cooling supply is not sufficient after switching off some of the operating chillers. This results in disordered chilled water distribution, leading to imbalanced thermal comfort sacrifices among building zones. In addition, a severe deficit flow problem might arise, causing increased energy consumption of the secondary pumps.

- The proposed reconfigurable control strategy offers a solution for managing the distribution of cooling supply effectively to address the above issues. This strategy can be implemented on conventional building automation systems adopting digital controllers commonly-used today, such as DDC and PLC.
- Test results show satisfactory control stability in valve opening control and proper chilled water distribution. This enables uniform space temperature distribution and thermal comfort control among the building zones during both demand response and rebound periods. The temperature deviation among the zones is controlled within 0.2 K for the majority of the time. Furthermore, proposed reconfigurable control achieves 11.6 % and 27 % of power demand reductions during demand response and rebound periods respectively, compared with that using conventional controls.

CRediT authorship contribution statement

Mingkun Dai: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Hangxin Li:** Supervision, Project administration, Funding acquisition. **Xiuming Li:** Software. **Shengwei Wang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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