WANG, Huilong; WANG, Shengwei. The impact of providing frequency regulation service to power grids on indoor environment control and dedicated test signals for buildings. Building and Environment, 2020, 183: 107217.

https://doi.org/10.1016/j.buildenv.2020.107217

The impact of providing frequency regulation service to power grids on indoor environment control and dedicated test signals for buildings

Huilong Wang[1,2] and Shengwei Wang[1,*]

[1] Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[2] Research Institute of Sustainable Urban Development, The Hong Kong Polytechnic University, Kowloon, Hong Kong

Abstract: Heating, ventilation and air-conditioning systems (HVAC), at demand side, have been regarded increasingly as promising candidates to provide frequency regulation service to smart power grids. To assess the performance of the frequency regulation service provided by the demand side, dedicated frequency regulation test signals have been proposed that are relatively demanding and critical to power grids considering the quality of the service provided by the demand side. However, other practical signals might be demanding and critical to buildings at the demand side considering the impact of the service on indoor environment control. In this study, a set of criteria is proposed to assess the demanding level of frequency regulation signals to power grids and buildings at demand side, respectively. The impacts of providing frequency regulation service (to power grids) on indoor environment control are quantified when HVAC systems are following practical signals with different demanding levels to buildings. The results show that indoor air temperature can have a relatively large offset when HVAC systems are following frequency regulation signals demanding to buildings. In addition, the indoor air temperature offset will increase when regulation capacity provided increases. Two dedicated test signals for buildings are therefore recommended to verify the environment control performance of buildings when providing frequency regulation service to power grids.

Keywords: HVAC system; building demand response; indoor environment control; ancillary services; grid-responsive building; smart grid.

** Corresponding author: Shengwei Wang, email: beswwang@polyu.edu.hk*

1. Introduction

The frequency of an electric power system must be strictly maintained within an acceptable narrow range by keeping the instantaneous balance of the power grid. It is conventionally guaranteed through frequency regulation provided at the supply side, which is one of the most important ancillary services. However, because of the intermittent nature, renewable power generation has placed great pressure on the reliability of power grids. This situation will deteriorate with the rapid increase of renewable power sources adopted in power grids [1]. Although building more power generators for reserve and incorporating more energy/power storage could relieve this pressure, the great investment is an unignorable obstacle [2]. Moreover, the problem of low average working hours of generators would further deteriorate due to the excessive generation capacity for reserves [3].

Recently, more policies and rules have been passed to encourage demand side resources to take part in the ancillary services market with monetary incentives [1, 4]. The process and mechanism for the demand side to provide frequency regulation service to power grids are elaborated as follows. The authorities of power grids calculate the "area control error" (ACE) which is the magnitude of power imbalance between the supply side and demand side. Then, the ACE is transformed and normalized to the frequency regulation signal, automatic generation control (AGC) signal (from -1 to 1), and send to participants involved [5]. To provide frequency regulation service to power grids, the demand resources are supposed to manipulate their power use timely and accurately to follow the AGC signal. Note that demand resources can bid different regulation capacities according to their own flexibility for feasible financial rewards. Therefore, even small power consumers are encouraged to take part in the ancillary services market [6]. A large number of small power consumers can result in a large regulation capacity collectively and can effectively help the power grids to relieve the power imbalance. In this way, the frequency of power grids can be maintained within an acceptable range. On the other hand, the authorities of power grids would test whether the power of participants at the demand side can follow the AGC signals properly. For example, the PJM (Pennsylvania-New Jersey Maryland Interconnection, regional transmission organization) uses performance scores to quantify the quality of frequency regulation service provided by the demand side participants [1]. In particular, PJM provides two kinds of AGC signals, including RegA signal (a type of AGC signal with a relatively low frequency) and RegD signal (a type of AGC signal with a relatively high frequency). To identify the qualification of demand resources in providing frequency regulation service, PJM selects two dedicated test signals on the basis of historical frequency regulation signals, including a 40-min RegA test signal and a 40-min RegD test signal. Service provider candidates are required to follow the corresponding test signals and their performance scores are assessed, including a delay score, a correlation score and a precision score as well as a composite performance score (i.e., the average of the first three scores). Candidates are only qualified to provide frequency regulation service when they can get a composite performance score not less than 0.75 [7].

Among various types of demand resources (service providers), heating, ventilation and air-conditioning (HVAC) systems in buildings are one of the most promising sources for providing frequency regulation service. It is because they account for a large proportion of electric energy consumption and have great power use flexibility. In the United States, buildings consume 74% of total electric energy [8] and HVAC systems in residential and commercial buildings consume about 16% of electric energy [9]. In Hong Kong, the building sector contributes over 90% of total electricity, and HVAC systems take up about 29.8% of electricity in non-residential buildings [10]. As mentioned above, to provide frequency regulation service to power grids, the demand resources are supposed to manipulate their power use to follow AGC signals. As a result, this will naturally affect the cooling/heating supply of HVAC systems, and eventually affect the indoor environment control in buildings.

Many studies have studied the possibilities of using HVAC systems for providing frequency regulation. Chillers and heat pumps almost consume half of the energy consumption of the entire HVAC system [11]. They are therefore the most attractive components to be considered for providing frequency regulation. In the study conducted by Su and Norford [9, 12], a 200-ton chiller serving a medium-sized commercial building was utilized to provide frequency regulation service by resetting the chilled-water supply temperature setpoint. The reported composite performance scores were 0.89 when following the 40-min RegA test signal and 0.86 when following the 40-min RegD test signal. Both cases could meet the requirement of PJM. No appreciable impact on indoor air temperature was observed. In the study of Zhao et al. [13], the whole HVAC system (i.e., chillers, fans and water pumps) was used to provide frequency regulation service by modulating the indoor temperature setpoint, the performance scores achieved were between 0.7991 and 0.8957 under different working conditions. In the study of Cai and Braun [14, 15], a variable-speed packaged rooftop unit (RTU) and a split heat pump were utilized for regulation tests, which were performed in psychrometric chambers. The composite performance score could reach 0.88. It also reported that providing frequency regulation service had a negligible impact on indoor comfort. In the study of Kim et al. [16], integrated with an isolated microgrid, the simulation study demonstrated that the variable-speed heat pump could be effectively used to provide frequency regulation service and the occupant comfort could be ensured as well. In their later experimental study [17], a variable-speed heat pump was used to provide frequency regulation service. The supply water temperature setpoint was modulated to adjust the heat pump power use. The reported composite performance scores were between 0.77 and 0.81, which could also meet the requirement. More details of the methods used by existing studies and comprehensive introduction can be found in our previous review paper [8].

In summary, previous studies have shown that chillers are qualified to provide frequency regulation service with a negligible impact on indoor environment control. However, it is worth noticing that in previous studies, both the quality of frequency regulation service and the impact of providing frequency regulation service on indoor environment control were studied simultaneously in the condition of following the dedicated frequency regulation test signals (the 40-min RegA & RegD test signal) given by the power grid to assess service quality. These signals are relatively demanding/critical to the grid (in terms of the quality of frequency regulation service) among practical AGC signals. Therefore, it is suitable and reasonable to select them to test the quality of frequency regulation service. However, there is a large proportion of practical AGC signals that is more demanding/critical to buildings (in terms of the impact on indoor environment control) than these signals (i.e., the 40-min RegA & RegD test signals provided). As a result, it is more reasonable to select AGC signals demanding/critical to buildings to test the impact of providing frequency regulation service on indoor environment control. However, no study can be found on quantifying this impact considering various possible profiles of practical AGC signals, particularly those demanding to buildings.

This study, therefore, investigates systematically and comprehensively the impact of providing frequency regulation service on indoor environment control and proposes dedicated test signals for buildings to verify environment control performance when providing frequency regulation service. A set of criteria is first proposed to assess the demanding level of frequency regulation signals to power grids and buildings. Then, a frequency regulation signal demanding to buildings is selected based on the criteria for the purpose of assessing the impact of frequency regulation on indoor environment. This impact is further analyzed when following signals of different demanding levels to buildings providing different regulation capacities. Finally, two dedicated test signals for buildings are selected which can be used to assess building environment control performance when providing frequency regulation service.

2. Control strategy of HVAC systems for providing frequency regulation service

A control strategy of an HVAC system for providing frequency regulation service is developed as shown in Fig.1. The HVAC system concerned is set up based on an HVAC system in the International Commerce Centre (ICC) in Hong Kong, which is a typical HVAC system. Chillers are used to provide frequency regulation service in this study.

As shown in Fig. 1, a hierarchical control scheme for providing frequency regulation service is used, which consists of a power use following controller and a regulation bidding controller (as presented in the blue square). The function of the power use following controller is to determine reference power use, as the power use setpoint (P_{set}) of the chillers, according to Eq. (1). Here, AGC signal is given by power grids directly. P_b is the power use baseline, which refers to the power use of the chillers under conventional control without providing frequency regulation service. It represents the power use needed to meet the space cooling demand, which is determined by the regulation bidding controller. The regulation capacity (C_{reg}) is the modulation magnitude around the power use baseline (i.e., $P_b \pm C_{reg}$), which is also determined by the regulation bidding controller.

$$P_{set} = P_b + AGC\ signal \times C_{reg} \tag{1}$$

In this study, the chillers are used to provide frequency regulation service. To modulate the power use of the chillers, the indoor air temperature setpoint ($T_{in,set}$) and the outlet water temperature setpoint of the chillers ($T_{chiller,out,set}$) are adjusted, which is a method commonly used in previous studies.

In practice, frequency regulation belongs to the hour-ahead market (e.g., in the PJM), the baseline and regulation capacity should be dynamically reset at the beginning of each hour according to the system working conditions. In this study, to investigate the impact of providing frequency regulation service under different conditions, the regulation capacity and the power use baseline are determined directly.

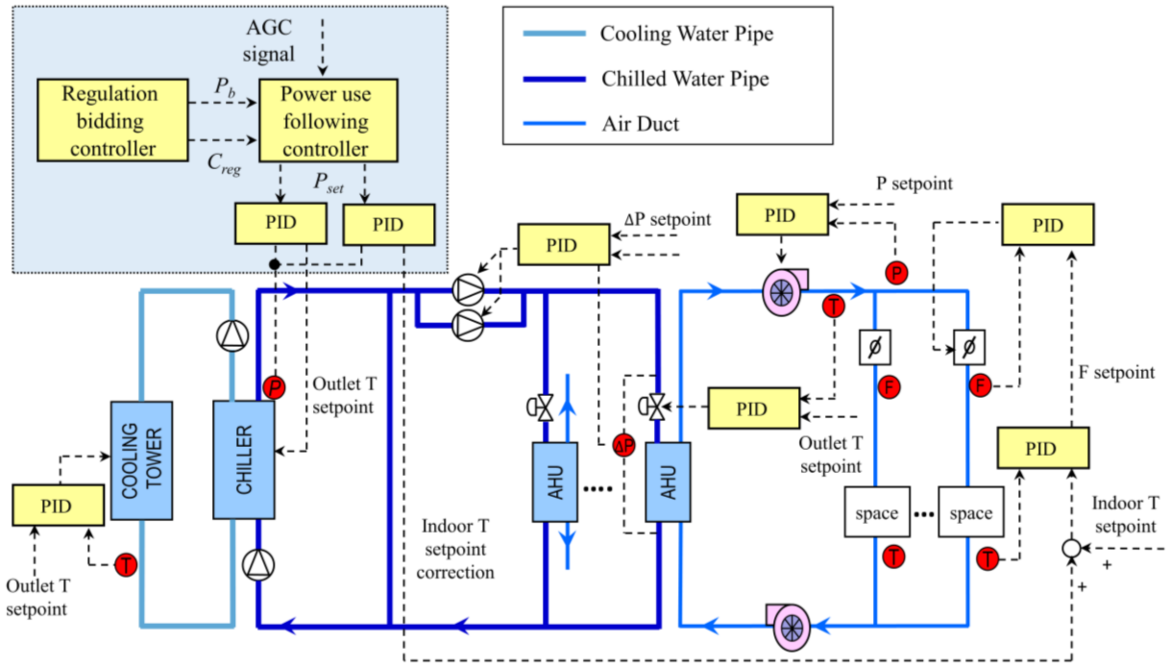

Fig. 1. Control strategy for chillers in providing frequency regulation service.

3. Demanding levels of frequency regulation signals to power grids and buildings

As mentioned in the Introduction, frequency regulation signals (i.e., AGC signals) reflect the magnitude of power imbalance between the supply side and demand side. Some signals could be demanding to power grids (in terms of the quality of frequency regulation service). Some signals could be demanding to buildings (in terms of the impact on indoor environment control). In this section, a set of criteria is proposed to quantify the demanding level of an AGC signal to power grids and buildings, respectively.

3.1. Demanding level of frequency regulation signals to power grids

Technically, to provide frequency regulation service with a qualified performance score, the actual power use of the resources should follow the reference power use (i.e., power use setpoint) timely and accurately. As a result, a more volatile AGC signal is more demanding for the demand side to get a qualified performance score required by the supply side. In this study, "fluctuation velocity" is adopted based on the concept of "mileage" from PJM [14], which can reflect the volatility, and used to assess the demanding level of a signal to power grids, as shown in Eq. (2), where $s(i)$ is the value of the AGC signal at time i. t is the total time (in second). The fluctuation velocity is defined as the average speed the AGC signal traverses within a given period of time. Therefore, a signal with a larger fluctuation velocity is more demanding to power grids.

$$fluctuation\ velocity = \frac{\sum_{i=0}^{m} |s(i+1) - s(i)|}{t} \tag{2}$$

Fig. 2 shows the hourly fluctuation velocities of RegA & RegD signals in 2018. It can be observed that the fluctuation velocity of the RegD signal is obviously larger that than of the RegA signal. It indicates that the RegD signal is more volatile and is more demanding to power grids. Therefore, demand resources are required to respond faster when providing frequency regulation service following the RegD signal.

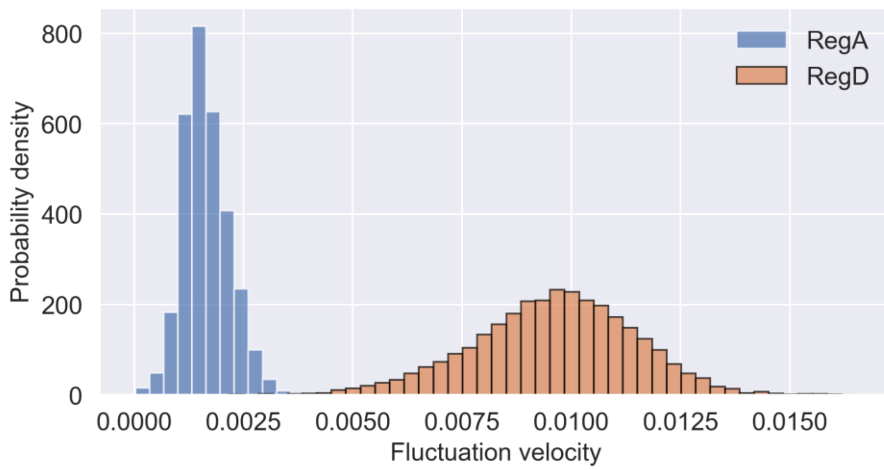

Fig. 2. Fluctuation velocity of RegA & RegD signal of each hour in 2018.

3.2. Demanding level of frequency regulation signals to buildings

The demanding level of a frequency regulation signal to buildings is reflected in its impact on indoor environment control. Particularly, a more demanding signal to buildings indicates that it is more likely to cause a larger indoor air temperature offset. Before introducing the criterion to assess the demanding level of the frequency regulation signals to buildings, the mechanism of the indoor air temperature offset when providing frequency regulation service is elaborated as follows.

According to Eq. (1), it can be found that the power use of the chillers is manipulated to deviate from the power use baseline when providing frequency regulation service. This would naturally affect the cooling supply of HVAC systems, eventually affecting indoor environment control in buildings.

It is also mentioned in Section 2 that the demand resources (i.e., frequency regulation service providers) should bid (i.e., reset) the power use baseline and regulation capacity at the beginning of each hour in the PJM market. This, on the other hand, also means that buildings have the opportunity to adjust their power use baseline to eliminate the indoor air temperatures offset caused in the previous hour. Therefore, the compounding effect of providing frequency regulation service on the indoor temperature is eliminated. Consequently, if the indoor environment control can be guaranteed within one hour, it can then be guaranteed for many consecutive hours to a large extent.

The AGC signal is not known when HVAC systems are bidding the power use baseline and regulation capacity to power grids at the beginning of each hour [18]. As a result, buildings face the risk of encountering different possible profiles of AGC signals in the following hour after bidding. As mentioned in the Introduction, the power use baseline is the power use needed to maintain the indoor air temperature setpoint in the following hour. Therefore, taking cooling for example, the signal above zero mainly causes a negative offset of indoor air temperature, while the signal below zero mainly causes a positive offset of indoor air temperature. Consequently, the positive (negative) hourly "maximum accumulated offset" (MAO) of the AGC signal, in principle, would most likely result in the negative (positive) "maximum temperature offset" (MTO) of indoor spaces within an hour. Thus, MAO is proposed in this study to quantify the demanding levels of the AGC signals to buildings. It is worth noticing that the bidding interval could be different in different electricity markets. For example, it is 15 minutes in the Swiss electricity market [19, 20].

The maximum accumulated offset (MAO) of the AGC signals can be calculated by Eq. (3) and Eq. (4), where, *m* is the total number of signal points within the period of time assessed. *x* is the time interval between two continuous signal points (normally from 2 to 4 seconds [21]). It is worth noticing that the offset can be positive or negative. As each point of the AGC signal is between -1 and 1, the range of signal MAO within a period of time is between -*mx* and *mx*. Particularly, "MAO = *mx*" means within this period of time, the power use setpoint is set as P_b+C_{reg} (according to Eq. (1)) continuously, which most likely causes the maximum indoor air temperature decrease (under cooling mode).

$$\max_{n} \left|\sum_{i=1}^{n} s(i)\right| \quad \{n \in \mathbb{Z} | 1 \le n \le m\} \tag{3}$$

$$MAO = x \cdot \sum_{i=1}^{n} s(i) \tag{4}$$

Take the 40-min RegA test signal for example, as shown in Fig. 3, this signal is updated once every two seconds and thus *m* is *1200*. According to Eq. (3), the maximum accumulated offset time point could be found at *n=1085*, as marked as time ‘A’ in the figure. The MAO of this signal is *-983.6*, which can be calculated using Eq. (4). This value is actually the area above zero minus the area below zero before time ‘A’. In principle, a signal with a larger absolute MAO is more demanding to buildings.

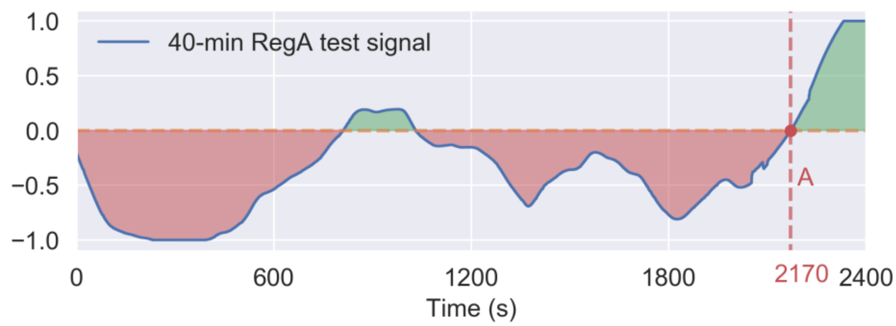

Fig. 3. The 40-min RegA test signal.

Fig. 4 shows the hourly maximum accumulated offset (MAO) of RegA & RegD of each hour in 2018. It can be observed that, compared with the MAO of RegD signal, a larger proportion of MAO of the RegA signal has a great absolute offset from zero. This indicates that the maximum temperature offset (MTO) of indoor spaces could be larger when following the RegA signal, compared with the RegD signal under the same working condition (i.e., power use baseline and regulation capacity). The figure also shows that most MAO of RegA is negative, indicating that temperature increase (under cooling mode) can be the main risk when providing frequency regulation service following the RegA signal.

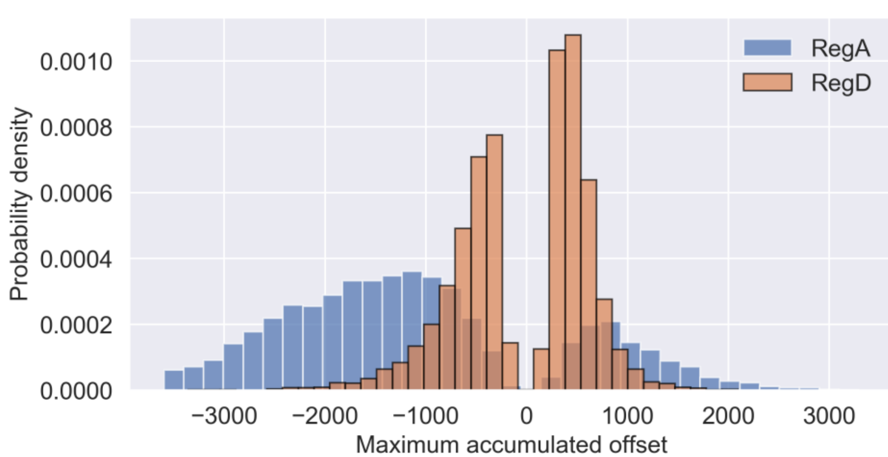

Fig. 4. Hourly maximum accumulated offset of RegA & RegD signals of each hour in 2018.

4. Test arrangement and test platform

4.1 Test arrangement

To provide a comprehensive analysis of providing frequency regulation service on indoor environment control, a series of simulation tests are conducted to accomplish the following three subtasks.

Subtask One - Study the impact of providing frequency regulation service on indoor environment control when following a test signal demanding to buildings, with results presented in Section 5. For this purpose, a test signal demanding to buildings is selected based on the criterion proposed in Section 3. This test signal is then used to quantify the impact of providing frequency regulation service on the indoor environment control. For comparison, the impact of providing frequency regulation service on indoor environment control when following the dedicated signal selected by power grids (i.e., 40-min RegA test signal) is also evaluated. This study mainly focuses on the RegA signal rather than the RegD signal. The reason is that the RegA signal is more demanding to buildings on indoor environment control, resulting in a large indoor air temperature offset, as mentioned in Section 3.2.

Subtask Two - Study the relationship between the demanding level of AGC signals to buildings and the impact of frequency regulation service on indoor environment control, with results presented in Section 6.1. For this purpose, tests are conducted by following historical hourly RegA signals in the whole year of 2018. This means that as many as 8,760 tests are conducted.

Subtask Three - Study the impact of regulation capacity on indoor environment control, with results presented in Section 6.2. For this purpose, tests are conducted by following historical hourly RegA signals in the whole year of 2018 with five different regulation capacities. This means that as many as 43,800 (i.e.,8,760×5) tests are expected.

In each test, the normal control (conventional feedback control without providing frequency regulation service) is maintained for 5 hours prior to the frequency regulation test. In this way, it can eliminate the impact of the initial condition of the room (due to the thermal inertia of walls and internal mass) and the initial condition of the HVAC systems (due to start-up) on the test results. The power use baseline is set as 737 kW in all the tests. The regulation capacity is set as

160 kW in all the tests except those studying the impact of the regulation capacity itself (for the Objective Three).

4.2 Test platform

As a large number of repetitive tests are required, a computer-based dynamic simulation test platform is constructed to set test settings and perform the tests automatically. Simulation tests are also considered as an effective and reliable approach for repetitive comparison tests, which can remove the interference of uncertainties in repetitive tests. In this study, the building model and the HVAC system models are built in TRNSYS 18 (32-bit) [22], and MATLAB 2014a (32-bit) [23] is used to manage the repetitive tests automatically. The test platform is shown in Fig. 5.

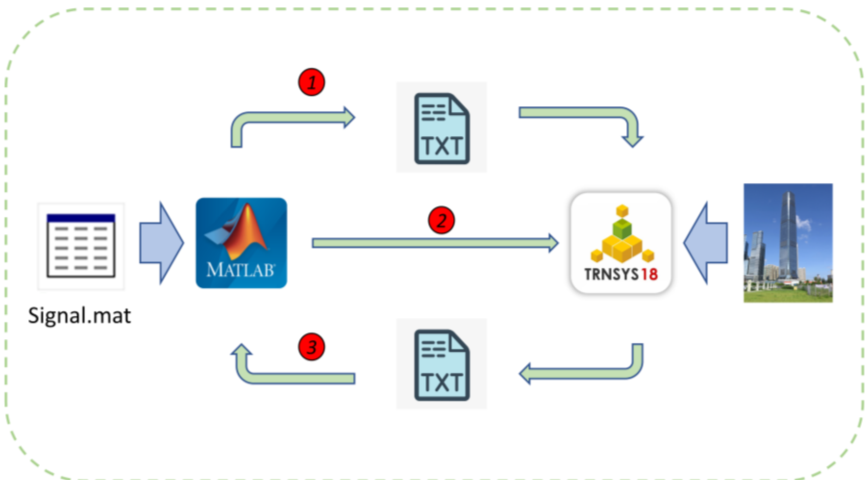

Fig. 5. TRNSYS-MATLAB co-simulation test platform

For the simulation tests, the data of the historical AGC signal in 2018 are saved to a MAT-file. Each test follows three steps. In the first step, the MATLAB extracts an hourly AGC signal from the MAT-file and writes in an input file (in text form) of TRNSYS. In the second step, the MATLAB runs the TRNSYS. In the last step, the MATLAB extracts the indoor air temperature from the output file (in text form) of TRNSYS for analysis.

The simulation interval in this study is one second. It is found that each test takes about 50 seconds. Thus 8,760 cases would take about 5 days. To reduce computation time, parallel computing is used. The tests are conducted on a computer with Intel Core i7 CPU including eight cores. In this study, five cores are used simultaneously which can significantly reduce the computation time.

The test platform is constructed based on the International Commerce Centre (ICC) in Hong Kong. The building is about 490 m high with a total floor area of approximately 321,000 m^2 served by a typical air-conditioning system including six identical chillers. The rated cooling capacity and power consumption of each chiller are 7230 kW and 1270 kW respectively [24]. In this study, only one chiller, corresponding to hypothetical one-sixth area, is used for providing frequency regulation service. The models of the building and the HVAC system are introduced as follows.

4.2.1 Dynamic models of building

As mentioned in the Introduction, providing frequency regulation service could affect the cooling/heating supply of HVAC systems which eventually affect the indoor environment control. Actually, indoor temperature changes can directly affect cooling load (e.g., fresh air cooling load, heat transfer between the air and walls & internal mass), this can in reverse affect the dynamics of the indoor temperature. This phenomenon would be more significant when the indoor temperature offset is larger. Therefore, a detailed room model is required to precisely describe the dynamic thermal behavior of the building. In this study, the model Type 56 in TRNSYS is used. It is a detailed physical model that is popular and widely used in the research area of building simulation. The settings in the building model are presented as follows.

Envelope: External walls (10mm gypsum plaster, 100 mm concrete 10mm cement/sand render, 5mm mosaic tiles and light color semi-glossy paint [25]) and windows (6mm single-glass) [26].

Internal mass: Many studies have pointed out that internal mass can significantly impact the flexibility of buildings [27, 28]. According to a review [29], a reasonable range for the internal mass density in office buildings is 10–100 kg/m^2 of net floor surface area. In this study, 100 kg/m^2 wood/plastic material (density: 800 kg/m^3, thermal conductivity: 0.2w/m·k, specific heat capacity: 1400 J/kg·k, thickness: 0.018 m) is set in the building model.

Internal heat gain: The design density of occupants is 9 m^2 per person. The design lighting power is 30 W/m^2. The design equipment power is 30 W/m^2. The internal gain from occupancy, lighting and equipment can be split into convective and radiative components (occupants heat gains: 40% latent heat, 20% convective and 40% radiative; lighting heat gains: 50% convective and 50% radiative (i.e., fluorescent lights); equipment heat gains: 67% convective and 33% radiative) [30].

Fresh air and infiltration: The building is supplied with fixed amounts of fresh air of 10 L/s per person. The building is relatively tight, thus the infiltration rate is set as 0.1 ACH (air changes per hour) [30].

4.2.2 Dynamic models of the HVAC system

Different from typical conventional demand response [31-33], frequency regulation service is in a very short timescale (i.e., seconds) [8]. Therefore, using steady-state models could more or less misrepresent the dynamic process of providing frequency regulation service [14]. In this study, dynamic models of the building and HVAC systems are used to describe the frequency regulation process and generate more reliable conclusions. Since a large number of repetitive tests are conducted, the dynamic models of components in HVAC systems used are developed by introducing time constants to the outputs of steady-state models. This kind of dynamic model belongs to the filter model which can substantially reduce the time consumption of simulation tests [34]. The kind of model was also used by a previous study in which also a chiller was used to provide frequency regulation service [16].

Chiller: The power use of chillers under steady state conditions can be calculated by Eqs. (5)-(9). Where, Q_{load} is the cooling load of the chiller. m_{chw} represents the flow rate of chilled water. Cp_{chw} is the specific heat capacity of water. $T_{chw,in}$ and $T_{chw,out}$ are the inlet and outlet chilled water temperature respectively. The part load ratio (PLR) is the ratio of the Q_{load} to the chiller rated capacity ($Capacity_{rated}$). The coefficient of performance (COP) can be obtained from Eqs. (7)-(8). Where, COP_{rated} is the rated COP and α is relative efficiency to correct the rated COP under different PLRs, which is obtained from manufacturers [35, 36]. Accordingly, the power use of the chiller at steady state (P_s) can be finally obtained by Eq. (6). The transient characteristics of the chiller are extracted from the coupled nonlinear differential equations proposed by He [37], which are based on the mass, momentum, and energy balances of the refrigerant flowing through a heat exchanger tube [16]. According to the experimental study conducted by He [37], in the frequency domain, the change of power use (P) (corresponding to the compressor speed [9]) and $T_{chw,out}$ can be approximated by the first-order transfer function of the change of the chilled water outlet temperature setpoint $\Delta T_{chw,out,set}(s)$. The transient behavior of the chiller can be then represented by Eqs. (10)-(11). The power use and $T_{chw,out}$ in real-time is described by Eqs.(12)-(13) eventually.

The time constant is set as 1 minute. Other coefficients, such as *a* and *b*, can be obtained according to the steady-state performance of the chiller.

$$Q_{load} = m_{chw} \cdot Cp_{chw} \cdot (T_{chw,in} - T_{chw,out}) \quad (5)$$

$$PLR = \frac{Q_{load}}{Capacity_{rated}} \quad (6)$$

$$\alpha = n_1 \cdot PLR^3 + n_2 \cdot PLR^2 + n_3 \cdot PLR + n_4 \quad (7)$$

$$COP = COP_{rated} \cdot \alpha \quad (8)$$

$$P_s = \frac{Q_{load}}{COP} \quad (9)$$

$$\Delta P(s) = \frac{a}{s+T} \cdot \Delta T_{chw,out,set}(s) \quad (10)$$

$$\Delta T_{chw,out}(s) = \frac{b}{s+T} \cdot \Delta T_{chw,out,set}(s) \quad (11)$$

$$P(t) = P_s + \Delta P(t) \quad (12)$$

$$T_{chw,out}(t) = T_{chw,out,0} + \Delta T_{chw,out}(t) \quad (13)$$

Pump and fan: In this study, the power use of pumps and fans are neglected for simplicity. It is a common simplification when using chillers for providing frequency regulation service [9, 12, 38]. In fact, many pumps and fans are constant-speed devices in practical HVAC systems and their power uses are nearly constant.

Air handling unit (AHU): The steady-state characteristics of AHUs are described by Type 124 in TRNSYS. According to the experimental studies on AHUs [34, 39, 40], the transient behavior of AHUs can be described by first-order transfer functions. Therefore, similar to chillers, the dynamic behavior of AHUs can be obtained by introducing a time constant (set as 12 seconds in this study) to the outputs of the steady-state model.

Water and air pipeline: The dynamic behaviors of air flow and water flow are mainly affected by the frequency change of the input power (for variable-speed pumps and fans). According to our previous experimental study [41], after a step change of the frequency of the pump, it only takes 2 seconds for the water flow to return a new steady-state condition. Thus, a moving average method [42] is used to represent the dynamic behaviors of water flow and air flow. Here, it is assumed that the water pipeline and air pipeline have similar dynamic behaviors. The travel time of the water in the water loop and the travel time of air in the air loop are also considered as they could also have impacts on the response time of chiller power use. These times are estimated based on the practical information of the ICC building.

5. Impact of providing frequency regulation service on the indoor environment control when following a signal demanding to buildings

5.1. Selection of the test signal

According to the criterion proposed in Section 3, the signal which is demanding to buildings most likely has a large maximum accumulated offset. Based on this criterion, a 60-minute historical RegA signal for the 16th hour in the 213th day in 2018 is selected as the signal extremely demanding to buildings (namely 60-min $RegA_{B99}$ test signal). This test signal ($RegA_{B99}$) is more demanding to buildings than 99% of all the historical hourly RegA signals in 2018. The 40-min RegA test signal (given by the power grid) and the 60-min $RegA_{B99}$ test signal are presented and compared in Fig. 6. It can be observed in the figure that the 60-min $RegA_{B99}$ test signal almost remains at -1 in the whole hour.

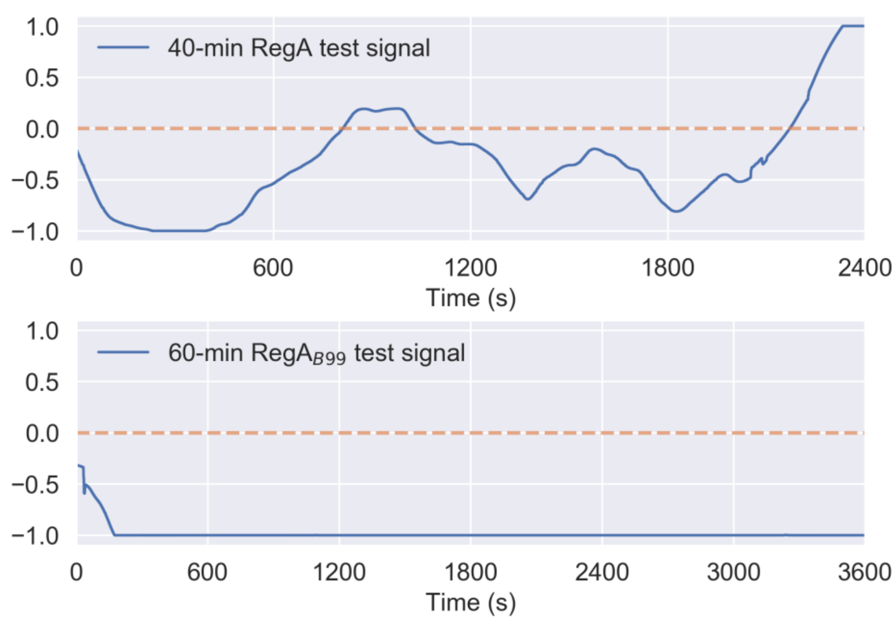

Fig. 6. The 40-min RegA test signal and the 60-min $RegA_{B99}$ test signal.

The demanding level of these two test signals to power grids and buildings are shown and compared in Fig. 7. As can be observed in Fig. 7(A), the 40-min RegA test signal (abbreviated as RegA in the figure) is more demanding to power grids than most practical hourly RegA signals throughout the year. It is natural and quite reasonable as power grids concern more about the quality of frequency regulation service to power grids. Selecting a relatively demanding signal as an “official” test signal can guarantee the practical quality of frequency regulation service provided. However, this signal is quite moderate to buildings and is not representative as the test signal to assess the impact of providing frequency regulation service on buildings at the demand side. As shown in Fig. 7(B), there is a large proportion of signals through the year that is more demanding to buildings than the 40-min RegA test signal.

On the contrary, the selected $RegA_{B99}$ test signal is actually quite moderate to the gird side for demand resources to provide high-quality frequency regulation service. However, it is very demanding and critical to buildings. The calculated maximum accumulated offset is *-3536.3*, which is very close to its lower limit (*-3600*).

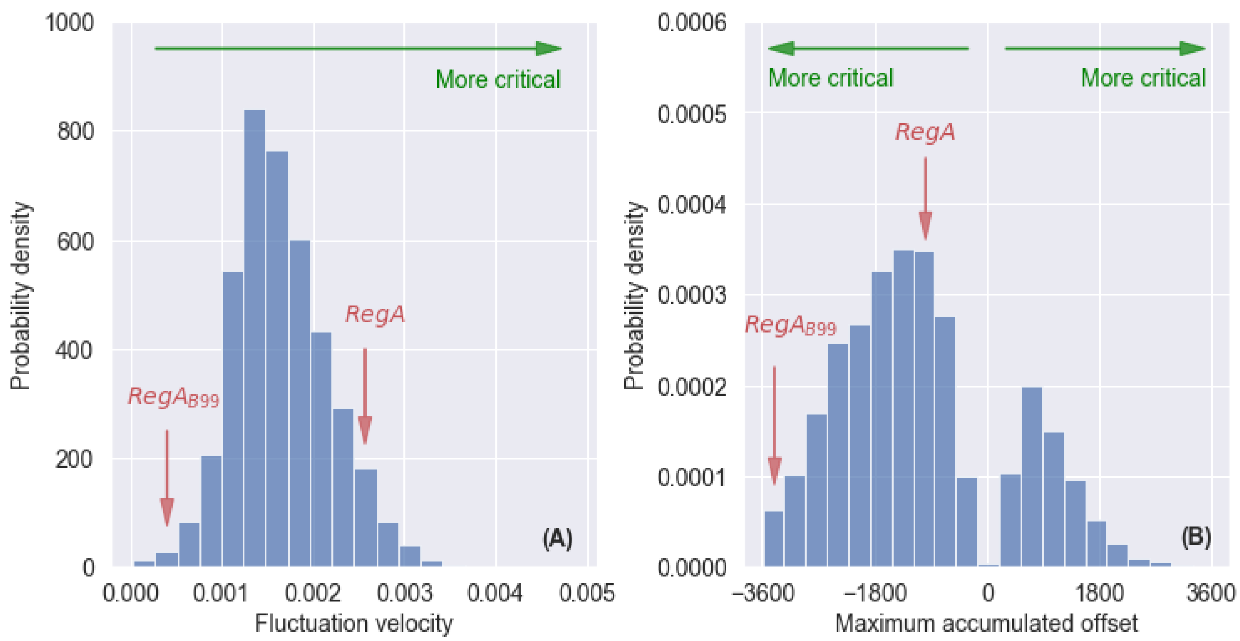

Fig. 7. Demanding levels of the 40-min RegA test signal and the 60-min $RegA_{B99}$ test signal to power grids and buildings.

5.2. Test results when following a test signal demanding to power grids

For comparison purposes, the frequency regulation test is conducted first when following the 40-min RegA test signal, a dedicated test signal relatively demanding to power grids selected by power grids.

The reference power use (the power use setpoint) and actual power use in the test are shown in Fig.8. The quality of the frequency regulation service is assessed using performance scores adopted in the PJM manual [7], including delay score (S_d), correlation score (S_c), precision score (S_p) as well as the composite performance score (i.e., the average of the first three scores).

The composite score of this test obtained was 0.901 (correlation score: 0.994, delay score: 0.920, precision score: 0.789). This composite score was higher than 0.75, indicating that the frequency regulation service provided by the chiller can fulfill the requirement set in the grid regulation standard. This is consistent with the conclusion of previous studies.

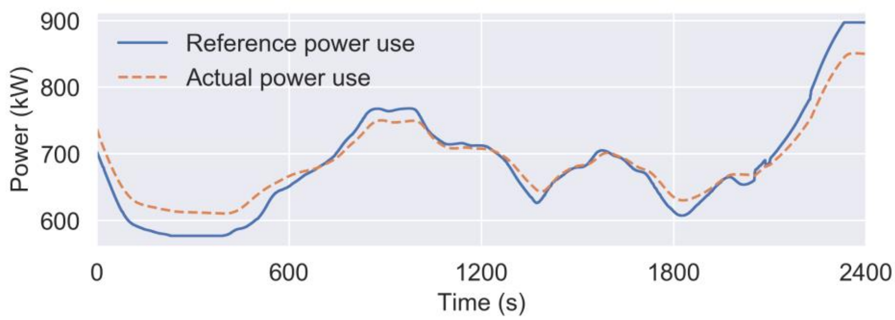

Fig. 8. Reference power use and actual power use of the chiller when following the 40-min RegA test signal.

Fig. 9 shows the 40-min RegA test signal and the indoor air temperature in the frequency regulation test. It can be observed from the figure that the test signal fluctuates between positive and negative regions. This makes the power use of the chiller higher and lower than the power use baseline within a limited period of time, neutralizing their impacts on indoor temperature. The indoor air temperature setpoint was set as 24 °C. As shown in the figure, the indoor air temperature reached its maximum value near time *B*, corresponding to the time when the test signal reached its maximum accumulated offset. The temperature only increased by 0.67 K at most, which did not impact thermal comfort significantly. This result is also consistent with that of the previous studies, i.e., providing frequency regulation has a negligible impact on indoor comfort when following the 40-min RegA test signal.

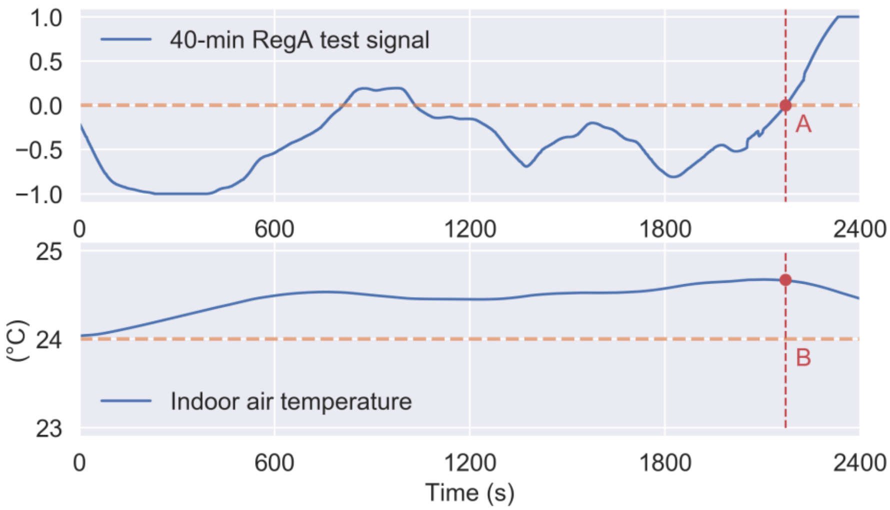

Fig. 9. 40-min RegA test signal and the indoor air temperature.

5.3. Test results when following a test signal demanding to buildings

Fig. 10 shows the signal demanding to buildings (i.e., the 60-min $RegA_{B99}$ test signal) and the indoor air temperature in the test under the same working condition (i.e., power use baseline and regulation capacity) when following the 40-min RegA test signal. As shown in Fig.10, the indoor air temperature increased significantly and reached up to 26.07 °C at the end of the test. This temperature might have exceeded the comfort range. This indicates that providing frequency regulation service may have a non-negligible effect on the thermal comfort of occupants when following the AGC signal that is demanding to buildings.

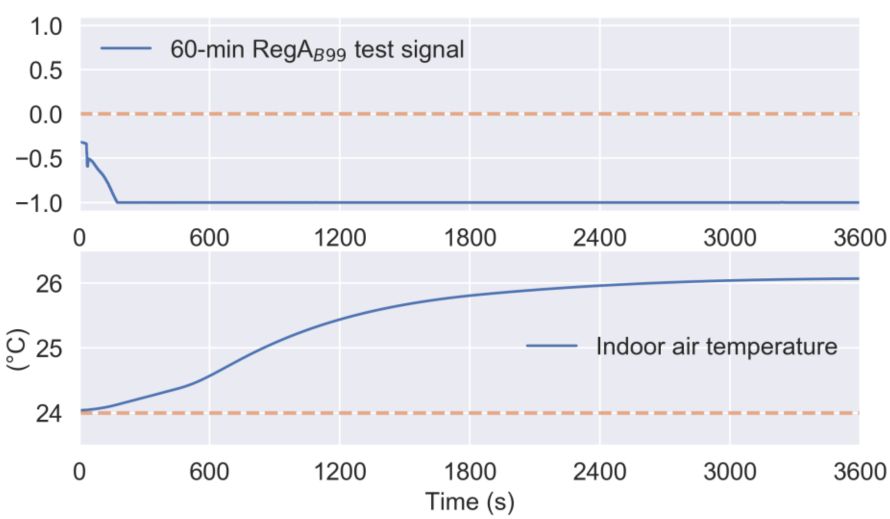

Fig. 10. 60-min $RegA_{B99}$ test signal and the indoor air temperature.

6. Impact quantification of frequency regulation service on indoor environment control

Section 5 has demonstrated the possibility that providing frequency regulation service can affect the thermal comfort of occupants. This section presents a detailed study on the relationship between the demanding level of AGC signals to buildings and the impact of frequency regulation service on indoor environment control. In addition, the effect of regulation capacity is also investigated.

6.1. Relationship between demanding level of AGC signals and impact on indoor environment control

Tests are conducted by following historical hourly RegA signal in the whole year of 2018. These hourly RegA signals have very different demanding levels to buildings. Fig. 11(A) shows the relationship between the hourly maximum accumulated offset (MAO) of the RegA signal in 2018 and the hourly maximum temperature offset (MTO) of the indoor space. Fig. 11(B) shows the probability distribution of hourly MTO of the indoor space. It has two humps, including a negative part and a positive part. It can be observed that the temperature increase (i.e., positive part) is the main risk when providing frequency regulation service following the RegA signal. Particularly, about 32% of the hours in the year could face the risk of having the absolute MTO larger than 1.5 K.

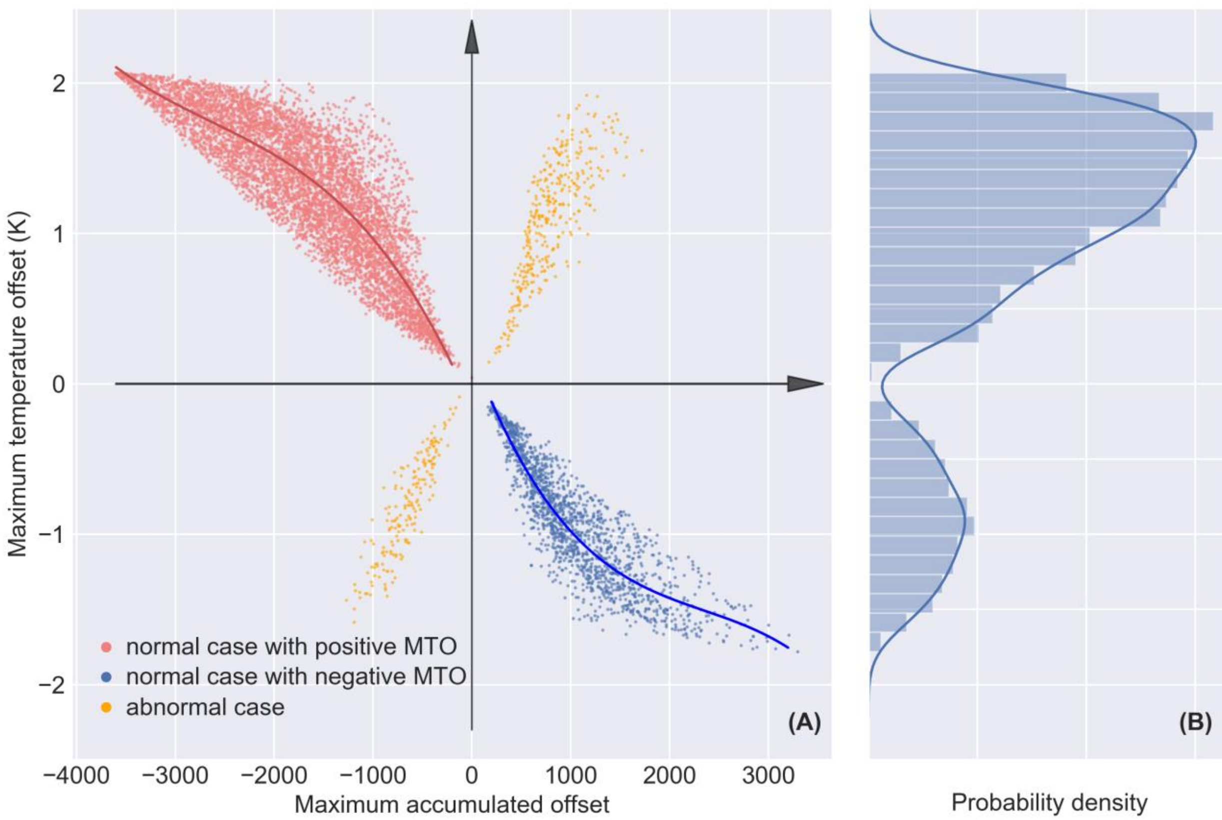

Fig. 11. Hourly maximum accumulated offset of RegA signal and hourly maximum temperature offset of the indoor space when providing frequency regulation service

As shown in Fig. 11(A), for the cases represented by red dots and blue dots, the hourly MAO of the RegA signal and hourly MTO of the indoor space have opposite signs. This phenomenon is quite natural and reasonable. The negative hourly MAO of RegA signal would lead the system to consume less power than that in the scenario under conventional control. Less power consumption indicates a decrease of cooling supply, resulting in a positive offset of the indoor temperature. It is also easy to understand that the negative hourly MTO of the indoor space is corresponding to the positive hourly MAO of the RegA signal. However, the yellow dots show a quite different phenomenon. Both the hourly MAO of the RegA signal and hourly MTO of the indoor space are positive or both of them are negative (i.e., the same sign). This phenomenon may result from two reasons. One reason is that the actual power use cannot follow the reference power use (power use setpoint) perfectly. For example, although technically more power use is required, the actual power used may be less. Another reason is that the relationship between the actual power use and cooling supply is nonlinear. For example, although technically more total power is used, the total cooling supply may be less.

It can also be observed in Fig. 11(A) that, the hourly MTO of the indoor space changes relatively quickly with the increase of the absolute hourly MAO of the RegA signal. However, this trend slows down when the absolute hourly MAO of the RegA signal increases further. This is due to the impact of indoor air temperature to the cooling load. Take the cases represented by red dots for example, when the indoor air temperature increases, the internal mass and walls would absorb more (or release less) heat from/to the indoor air. The fresh air cooling load also decreases. The cooling load of the building, therefore, would decrease, which slows down the increasing trend of indoor air temperature.

6.2. Impact of regulation capacity on indoor environment control

In practice, one building could bid different regulation capacities when providing frequency regulation service. Different regulation capacities provided could also affect indoor environment control. It is worth noticing that the AGC signal has both positive and negative parts. Technically, chillers can at most provide 50% of their rated power for providing frequency regulation service.

To study the impact of regulation capacity on indoor environment control, tests are conducted by following historical hourly RegA signals in the whole year of 2018 with five different regulation capacities, from 60 kW to 260kW (from about 5% to 20% of the chilled rated power) with an interval of 50kW. This means that as much as 43,800 (i.e.,8,760×5) cases are required. To reduce the computation time, it is expected that fewer cases/hours in 2018, rather than 8760 cases, are used while it can still generate a representative probability distribution of the hourly maximum temperature offset (MTO) of the indoor space. In this study, Hellinger distance is introduced which can quantify the similarity between two probability distributions. Eq. (14) shows the Hellinger distance for two discrete probability distributions $P = (p_1, p_2, \ldots p_k)$ and $Q = (q_1, q_2, \ldots q_k)$ [43]. The range of Hellinger distance is from zero to one. Zero indicates that these two probability distributions are the same while one means they are completely different. In this study, it is found that the Hellinger distance between the probability distribution of 2000 cases (randomly selected) and the probability distribution of full (8760) cases is small enough (less than 0.05). Therefore, for each regulation capacity, 2000 hourly RegA signals are finally used to generate the probability distribution of the MTO of the indoor space.

$$H(P, Q) = \frac{1}{\sqrt{2}}\sqrt{\sum_{i=1}^{k}(\sqrt{p_i} - \sqrt{q_i})^2} \tag{14}$$

The probability distributions of hourly maximum temperature offset (MTO) of indoor space when following hourly RegA signals in 2018 under different regulation capacities are shown in Fig.12. As observed in the figure, with the increase of the regulation capacity, the probability distribution becomes flatter. This indicates that the risk of a large MTO of the indoor space would increase when regulation capacity provided increases. In particular, the MTO of the indoor space could even reach up to 3 K when the chiller provided 20% of its rated power for frequency regulation service. This amount of temperature offset, to some extent, could result in discomfort for occupants. It is also worth noticing that the internal mass is set as 100 kg/m^2 (normally from 10–100 kg/m^2 [29]) of the net floor surface area. The MTO of the indoor space could be even larger if there is less internal mass in the building.

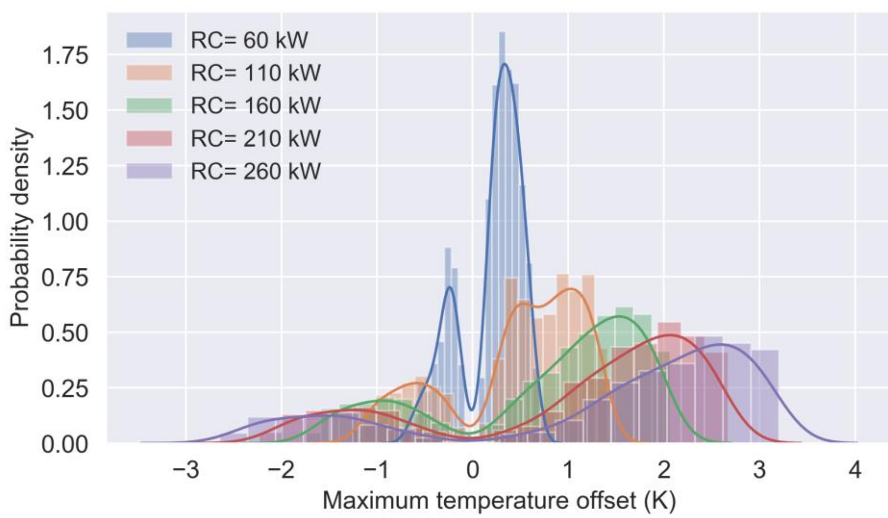

Fig. 12. The probability distribution of hourly maximum temperature offset of the indoor space when providing different regulation capacities.

7. Dedicated frequency regulation test signals for buildings to assess the environment control performance

From the viewpoint of power grids, dedicated frequency regulation test signals (the 40-min RegA & RegD test signal) which are relatively demanding to power grids are selected and used to assess the quality of frequency regulation service. This can guarantee the practical quality of frequency regulation service. At the same time, this can simplify the process of verifying the qualification of candidates of demand resources in providing frequency regulation service.

Referring to the implementation of power grids, two dedicated test signals for the buildings are selected which can be used to assess building environment control performance when providing frequency regulation service, as shown in Fig. 13. The first signal (60-min RegA$_{B99}$ test signal) is the signal used in Section 5 which is more demanding to buildings than 99% of all the historical hourly RegA signals in 2018. Another test signal (60-min RegA$_{B75}$ test signal) which is relatively less demanding, i.e., more demanding to buildings than 75% of all the historical hourly RegA signals in 2018.

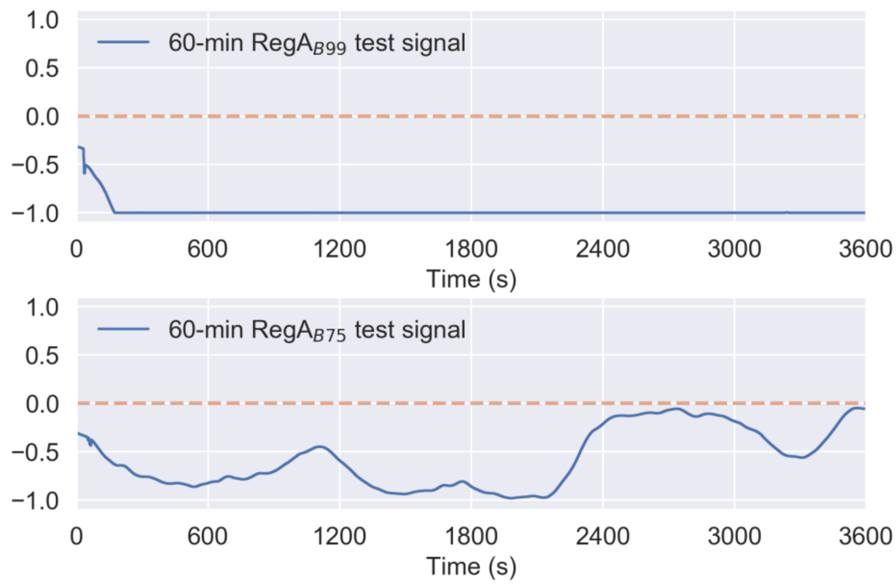

Fig. 13. Two dedicated test signals for buildings to assess the environment control performance when providing frequency regulation service.

These test signals are recommended for assessing building environment control performance (i.e., hourly maximum indoor air temperature offset) when providing frequency regulation service in applications. The 60-min RegA$_{B75}$ test signal is recommended for normal scenarios considering the performance of building indoor environment control, while the 60-min RegA$_{B99}$ test signal is recommended for the cases when the indoor environment control quality is critical. Moreover, under a given limitation of the hourly maximum indoor air temperature offset, the upper limit of regulation capacity in the term of the impact on indoor environment control can be determined. It is also worth noticing that there are other limitations of regulation capacity, such as the working range of devices [8, 21, 44].

8. Conclusion

In this paper, a set of criteria is proposed to assess the demanding levels of frequency regulation signals to power grids and buildings. Based on the criteria, a test signal demanding to buildings is selected to assess the impact of providing frequency regulation service on indoor environment control. This study further investigates the relationship between the demanding levels of frequency regulation signals to buildings and the impact of frequency regulation service on indoor environment control. The effect of regulation capacity on indoor environment control is also investigated. Finally, two dedicated test signals for buildings are recommended as the test signals for assessing the environment control performance of buildings when providing frequency regulation service. The main conclusions are summarized as follows.

- The proposed "fluctuation velocity" can be used to assess the demanding levels of frequency regulation signals to power grids effectively. A signal with a larger fluctuation velocity is more demanding to power grids.
- The proposed "maximum accumulated offset" (MAO) can be used to assess the demanding levels of signals to buildings effectively. In general, a frequency regulation signal with a larger absolute MAO is more demanding to buildings.
- Compared with the MAO of the RegD signal, a larger proportion of MAO of the RegA signal has a large absolute offset from zero. This indicates that the maximum temperature offset (MTO) of the indoor space could be larger when following the RegA signal, compared with the RegD signal under the same working condition (i.e., power use baseline and regulation capacity).
- Most MAO of RegA signal is negative. This makes the temperature increase (under cooling mode) to be the main risk when providing frequency regulation service following RegA signal.
- The impact of providing frequency regulation service may have a non-negligible effect on the thermal comfort of occupants when following a frequency regulation signal that is demanding to buildings. This problem is more serious when a large regulation capacity is provided. In the tests of this study, the MTO of the indoor space could even reach up to 3 K when the chiller provided 20% of its rated power for frequency regulation service.

- Due to the impact of indoor air temperature to the cooling load, the MTO of the indoor spaces changes relatively quickly with the increase of the absolute MAO of the frequency regulation signal. However, this trend slows down when the absolute MAO of the frequency regulation signal increases further.

According to the practice of electricity markets, the frequency regulation service providers should obtain the qualification by tests following the dedicated test signals (e.g., the 40-min RegA test signal) specified from the viewpoint of the grid side. This study suggests that buildings should also have their own dedicated test signals (i.e., 60-min $RegA_{B75}$ test signal and 60-min $RegA_{B99}$ test signal) to assess building environment control performance prior to providing frequency regulation service.

Acknowledgements

The research presented in this paper is financially supported by a general research grant (152165/20E) of the Hong Kong Research Grant Council (RGC) and a research grant under strategic focus area (SFA) scheme of the research institute of sustainable urban development (RISUD) of The Hong Kong Polytechnic University.

Reference

[1] Zhao P, Henze GP, Brandemuehl MJ, Cushing VJ, Plamp S. Dynamic frequency regulation resources of commercial buildings through combined building system resources using a supervisory control methodology. Energy and Buildings. 2015;86:137-50.

[2] Shi J, Lee W-J, Liu X. Generation scheduling optimization of wind-energy storage system based on wind power output fluctuation features. IEEE Transactions on Industry Applications. 2018;54:10-7.

[3] Li W, Xu P, Lu X, Wang H, Pang Z. Electricity demand response in China: Status, feasible market schemes and pilots. Energy. 2016;114:981-94.

[4] Federal Energy Regulatory Commission, FERC Order 755, 2011, https://www.ferc.gov/whats-new/comm-meet/2011/102011/E-28.pdf. [accessed 16 Feb 2020]

[5] Callaway DS, Hiskens IA. Achieving Controllability of Electric Loads. Proceedings of the IEEE. 2011;99:184-99.

[6] He Hao AK, Yashen Lin, Prabir Barooah, and Sean Meyn. Ancillary service for the grid via control of commercial building HVAC systems. In: American Control Conference; 2013.

[7] PJM Manual 12:Balancing Operations https://www.pjm.com/-/media/documents/manuals/m12.ashx?la=en [accessed 16 Feb 2020]

[8] Wang H, Wang SW, Tang R. Development of grid-responsive buildings: Opportunities, challenges, capabilities and applications of HVAC systems in non-residential buildings in providing ancillary services by fast demand responses to smart grids. Applied Energy. 2019;250:697-712.
[9] Su L, Norford LK. Demonstration of HVAC chiller control for power grid frequency regulation—Part 1: Controller development and experimental results. Science and Technology for the Built Environment. 2015;21:1134-42.
[10] Hong Kong Energy End-use Data 2017. https://www.emsd.gov.hk/filemanager/en/content_762/HKEEUD2017.pdf [accessed 16 Feb 2020]
[11] Wang H, Xu P, Lu X, Yuan D. Methodology of comprehensive building energy performance diagnosis for large commercial buildings at multiple levels. Applied Energy. 2016;169:14-27.
[12] Su L, Norford LK. Demonstration of HVAC chiller control for power grid frequency regulation—Part 2: Discussion of results and considerations for broader deployment. Science and Technology for the Built Environment. 2015;21:1143-53.
[13] Zhao P, Henze GP, Plamp S, Cushing VJ. Evaluation of commercial building HVAC systems as frequency regulation providers. Energy and Buildings. 2013;67:225-35.
[14] Cai J, Braun JE. Laboratory-based assessment of HVAC equipment for power grid frequency regulation: Methods, regulation performance, economics, indoor comfort and energy efficiency. Energy and Buildings. 2019;185:148-61.
[15] Cai J, Braun JE. A regulation capacity reset strategy for HVAC frequency regulation control. Energy and Buildings. 2019;185:272-86.
[16] Kim YJ, Norford LK, Kirtley JL. Modeling and Analysis of a Variable Speed Heat Pump for Frequency Regulation Through Direct Load Control. Ieee Transactions on Power Systems. 2015;30:397-408.
[17] Kim YJ, Fuentes E, Norford LK. Experimental Study of Grid Frequency Regulation Ancillary Service of a Variable Speed Heat Pump. Ieee Transactions on Power Systems. 2016;31:3090-9.
[18] Fabietti L, Gorecki T, Qureshi F, Bitlisliogl u A, Lymperopoulos I, Jones C. Experimental Implementation of Frequency Regulation Services Using Commercial Buildings. IEEE Transactions on Smart Grid. 2016:1-.
[19] Qureshi FA, Lymperopoulos I, Khatir AA, Jones CN. Economic advantages of office buildings providing ancillary services with intraday participation. IEEE Transactions on Smart Grid. 2016;9:3443-52.
[20] Lymperopoulos I, Qureshi FA, Nghiem T, Khatir AA, Jones CN. Providing ancillary service with commercial buildings: The Swiss perspective. IFAC-PapersOnLine. 2015;48:6-13.
[21] Vrettos E, Kara EC, MacDonald J, Andersson G, Callaway DS. Experimental Demonstration of Frequency Regulation by Commercial Buildings – Part I: Modeling and Hierarchical Control Design. IEEE Transactions on Smart Grid. 2018;9:3213-23.
[22] Cheng Y, Zhang S, Huan C, Oladokun MO, Lin Z. Optimization on fresh outdoor air ratio of air conditioning system with stratum ventilation for both targeted indoor air quality and maximal energy saving. Building and Environment. 2019;147:11-22.
[23] Cui C, Zhang X, Cai W, Jing G. A gradient-based adaptive balancing method for dedicated outdoor air system. Building and Environment. 2019;151:15-29.
[24] Wang SW, Gao D-c, Sun Y, Xiao F. An online adaptive optimal control strategy for complex building chilled water systems involving intermediate heat exchangers. Applied Thermal Engineering. 2013;50:614-28.
[25] Philip C, Chow W. Energy use in commercial buildings in Hong Kong. Applied Energy. 2001;69:243-55.
[26] Hu M, Xiao F, Wang L. Investigation of demand response potentials of residential air conditioners in smart grids using grey-box room thermal model. Applied Energy. 2017;207:324-35.
[27] Chen Y, Xu P, Gu J, Schmidt F, Li W. Measures to improve energy demand flexibility in buildings for demand response (DR): A review. Energy and Buildings. 2018;177:125-39.

[28] Li W, Xu P, Wang H, Lu X. A new method for calculating the thermal effects of irregular internal mass in buildings under demand response. Energy and Buildings. 2016;130:761-72.

[29] Johra H, Heiselberg P. Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review. Renewable and Sustainable Energy Reviews. 2017;69:19-32.

[30] Wang SW, Xu X. Parameter estimation of internal thermal mass of building dynamic models using genetic algorithm. Energy Conversion and Management. 2006;47:1927-41.

[31] Vellei M, Le Dréau J. A novel model for evaluating dynamic thermal comfort under demand response events. Building and Environment. 2019;160.

[32] Aghniaey S, Lawrence TM, Sharpton TN, Douglass SP, Oliver T, Sutter M. Thermal comfort evaluation in campus classrooms during room temperature adjustment corresponding to demand response. Building and Environment. 2019;148:488-97.

[33] Cui B, Wang SW, Yan C, Xue X. Evaluation of a fast power demand response strategy using active and passive building cold storages for smart grid applications. Energy Conversion and Management. 2015;102:227-38.

[34] Zhou X, Braun J. A Simplified Dynamic Model for Chilled-Water Cooling and Dehumidifying Coils—Part 1: Development (RP-1194). HVAC&R Research. 2007;13:785-804.

[35] Kang J, Wang SW, Gang W. Performance of distributed energy systems in buildings in cooling dominated regions and the impacts of energy policies. Applied Thermal Engineering. 2017;127:281-91.

[36] Shan K, Wang SW, Gao D-c, Xiao F. Development and validation of an effective and robust chiller sequence control strategy using data-driven models. Automation in Construction. 2016;65:78-85.

[37] He X-D. Dynamic modeling and multivariable control of vapor compression cycles in air conditioning systems: Massachusetts Institute of Technology; 1996.

[38] Qureshi FA, Jones CN. Hierarchical control of building HVAC system for ancillary services provision. Energy and Buildings. 2018;169:216-27.

[39] Clark DR, May WB. HVACSIM+ building systems and equipment simulation program-user's guide. National Bureau of Standards, Washington, DC (USA). Building Equipment Div.1985

[40] Zhou X, Braun J. A Simplified Dynamic Model for Chilled-Water Cooling and Dehumidifying Coils—Part 2: Experimental Validation (RP-1194). HVAC&R Research. 2007;13:805-17.

[41] Wang H, Wang SW, Shan K. Experimental study on the dynamics, quality and impacts of using variable-speed pumps in buildings for frequency regulation of smart power grids. Energy. 2020:117406.

[42] Zhuang C, Wang SW. Risk-based online robust optimal control of air-conditioning systems for buildings requiring strict humidity control considering measurement uncertainties. Applied Energy. 2020;261.

[43] Lindsay BG. Efficiency versus robustness: the case for minimum Hellinger distance and related methods. The annals of statistics. 1994;22:1081-114.

[44] Vrettos E, Kara EC, MacDonald J, Andersson G, Callaway DS. Experimental Demonstration of Frequency Regulation by Commercial Buildings – Part II: Results and Performance Evaluation. IEEE Transactions on Smart Grid. 2018;9:3224-34.