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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

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Abstract: Renewable electricity generations have been growing rapidly in recent years worldwide as a result of efforts to address the global energy issue. However, it has also imposed increasing challenges on the balance of power grids due to their intermittent nature. Building sector, as the largest consumer, is expected increasingly to play an important role in providing ancillary services (AS) to relieve stress and reduce the needs of investment for power balance of the smart grids. Grid-responsive building therefore becomes a worthwhile and essential feature of buildings today and in the future. This paper provides an overview of the classification, benefits, applications as well as methods/technologies for HVAC systems in non-residential buildings to provide ancillary services, as fast responses (i.e., in the magnitude of seconds or minutes) to the needs of smart grids. In addition, the challenges of applications and potential solutions are investigated and summarized. The potential capacities of HVAC systems in the entire non-residential building sector in Hong Kong for providing frequency regulation (FR) and spinning reserve are also quantified.

Keywords: building demand response; ancillary services; grid-responsive building; energy-flexible building; smart grid.

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1. Introduction

Sustainable energy supply is a global challenge for the sustainable development of the human society. Power generation using renewable energy sources is considered as a promising solution to address this challenge worldwide. According to the statistics from International Renewable Energy Agency (IRENA), the global cumulative installed capacity of wind power and solar power generation had reached 513.939 GW and 390.625 GW by the end of the year 2017 [1]. And they are still growing at very high rates (20% per year for wind power and 60% per year for solar power) in recent years [2]. It is expected that the proportion of the renewable energy generations in power grids will be more significant in the near future. The stability of power grid requires the proper balance between the supply and the demand side at all time-scales. However, the increased proportion of renewable electricity generations has imposed great challenges on the power balance and reliability of power grids. The power generation may swing a lot due to their intermittent nature with the change of the weather condition [3, 4]. Moreover, with the use of more inverter-connected generation units, high penetration of renewable power generation which replaces conventional plants will also reduce the system inertia and hence may make a system more sensitive to disturbances [5]. Sometimes, the power reliability management center has to curtail the power generation from renewable energy sources to ensure the stability of the power grid. In China, the amount of solar energy curtailment was 7300 GWh in 2017, where unstable supply is one of the main reasons [6]. In 2016 in China, as much as 49.7 TWh of wind power was curtailed and China on average curtailed 17.1% of its wind power generation. The lost sales for power producers amounted to 18.7 billion RMB ($2.7 billion) [7]. Normally, the reliable operation of power grids is guaranteed by ancillary services (AS) provided at supply side. Here, according to the definition adopted by Federal Energy Regulatory Commission (FERC), ancillary services refer to those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system [8]. Some studies estimated that the accumulated renewable energy generations under the current rate would exceed the ability of the supply side (both the ramping rate and capacity) to provide ancillary services very soon [9]. Huge investment, if solving this problem from supply side as usual, cannot be avoided either by building energy/power storages[10] or by setting up more generators for reserve, and the annual working hours of generators will decrease dramatically due to the rapid increase of installed capacity. Actually, the average working hours of generators in China has decreased to 4286 hours in 2014 [11].

In recent years, more and more attentions have been paid on encouraging demand side to contribute for the power balance of power grid and to participate in the ancillary services, that requests the buildings, as the largest power consumer along with energy storage capability, to be capable to respond to the requirements of power grids and change their power demand profiles, usually known as demand response (DR). The co-author of this paper, therefore, proposed the concept of "grid-responsive building", expecting future buildings to be "grid-friendly" and "grid-responsive" [12]. "Grid-friendly" means that a building can work in synergy with the power grid and avoid putting additional stress on the balance of the power grid. "Grid-responsive" means that a building can respond to the needs and requests of the smart grid, contributing to the grid power balance timely and effectively, in order to enhance the reliability of the power grid and optimize the overall efficiency of the grid-building ecosystem.

Although both regarded usually as subcategories within the generic concept of "demand response", buildings which contribute to ancillary services and "conventional demand response" are different in terms of objective and technology involved. That leads to the need for differentiating the contributions of buildings to power grids. The main objective of "conventional demand response" (categorized in this paper) of buildings is to contribute for the operation efficiency improvement of power grids, and the technical requirements are more challenging in capacity and duration. Significant peak load reduction is expected over a relatively long period of time. The main objective of "ancillary services" of buildings is to contribute to the reliability enhancement of power grids [8]. This requests buildings to be able to manipulate their power demand profiles even in the time scale of seconds, in order to relieve the imbalance of power supply and demand. In ancillary services programs, more concerns are raised on the response speed and accuracy, requiring power demand to be changed in a short period of time for a certain amount to compensate the deviation in power balance of a power grid. When adopting such differentiation, part of conventional demand response functions, such as prescheduled demand response or response to fixed changes of price, belong to the grid-friendly feature. The grid-responsive feature involves ancillary services and the other part of conventional demand response functions, such as demand response to real-time pricing or unscheduled demand reduction requests of smart grids. This new feature is closely related to another new concept of energy flexible building [13-15], while the concept of grid-responsive building would be more precise to focus on the most important needs for buildings to be flexible in using electrical energy and to be responsive to power grids.

Currently, many studies have summarized the issues associated to "conventional demand response", including both prescheduled and real-time means [16, 17]. This paper therefore focuses on the new potential functions and contributions of grid-responsive buildings: i.e., ancillary services or fast demand responses. In buildings, HVAC (heating, ventilation and air conditioning) systems are the preferable systems to provide ancillary services because they naturally interconnect electrical energy and thermal energy systems and, at the same time, buildings inherently have thermal energy storage capacities. In recent years, many efforts have been paid on studying the use of HVAC systems in non-residential buildings for providing ancillary services [9, 18-37] while very few studies can be found on residential buildings [38, 39]. Different components in HVAC systems are tested for various types of ancillary services. Many advanced control strategies are also proposed to address the newly-rising challenges of such applications [22, 23, 28-30, 35, 40, 41]. A few studies also addressed the potentials (capacities) of grid-responsive buildings for ancillary services [19-22, 42]. However, no comprehensive study or systematic review can be found in the literature focusing on this topic from a technical viewpoint.

This paper therefore attempts to provide a comprehensive study on the opportunities, technologies, challenges and capabilities of HVAC systems in non-residential buildings for providing ancillary services in smart grids. The first part of this paper presents a systematic review on the existing studies concerning the opportunities, technologies and challenges for buildings in providing ancillary services. The second part presents an original quantitative study on the capabilities of centralized HVAC systems in providing ancillary services. The rest of this paper is organized as follows.

Section 2 introduces the classification of ancillary services that could be provided by HVAC systems. The difference of these services (in normal operation and contingency operation) and their comparison with conventional demand response are also analyzed. In Section 3, the benefits of building HVAC systems in providing ancillary services are introduced and elaborated. Section 4 presents the applications and associated technologies for demand side to provide these services. In Section 5, the challenges of current technologies and potential solutions are investigated and summarized. In section 6, taking Hong Kong as a case, the capacities of centralized HVAC systems non-residential buildings to provide frequency regulation and spinning reserve are quantified and evaluated using two different methods. Conclusions and recommendations are given in the last section.

2. Outline of ancillary services, demand response and potentials of building HVAC systems

2.1 Ancillary services that can be provided by HVAC systems in buildings

Table 1 Main ancillary services that can be provided by demand side and their requirements

Operation condition	**Service Type**	**Requirement**					**Means of services at supply side**
		Speed of respond	**Time of full response**	**Duration of response**	**Service frequency**	**Capacity required**	
Normal Operation	Frequency Regulation	seconds	about 3 minutes	Energy neutral in 15 minutes	continuous	1% [42, 43]	Rotating inertia of all synchronous generators Frequency responsive governors Automatic generation control (AGC) [44]
	Load following	1 minute		Energy neutral in a few hours	continuous		
Contingency Operation	Spinning reserve	1 minute	Less than 10 minutes	<30 minutes [43]	~ 10-hundreds times a year [45]	2.5%-3% [42]	Spinning reserve generator Non-spinning reserve generator
	Non-spinning reserve	10 minute	Less than 10 minutes	>30 minutes	~ 10 to hundreds times a year [45]	2.5%-3% [42]	

Ancillary services could be categorized into six groups according to FERC [8]. Among different types of ancillary services, in current markets, demand side could provide part of them associated to two operation conditions, normal operation [3, 43] and contingency operation [42, 46]. Table 1 presents a summary on the main ancillary services which demand side could provide, and their requirements on five aspects including: speed of response, time of full response, duration of response, service frequency and capacity requirement. The corresponding means of these ancillary services, if provided at the supply side, are also shown in the table.

2.2 Demand response vs ancillary services provided by demand side

Demand response [47], which has received great attention over the last decades in building field besides power grid field, is often confused with ancillary services because they indeed share some characters. However, there are major differences between these two concepts/functions. A wider perspective of demand-side management and its categories, technologies as well as their functions are illustrated in Fig.1. From the perspective of motivation, the demand response can be divided into price-based programs and incentive-based programs [16, 48]. Some incentive-based programs which aim to increase the reliability of grid belong to ancillary services [17].

In the building field, up to today, demand response usually refers to some incentive-based programs including ”*demand bidding/buyback”*, ”*emergency programs”* and ”*interruptible programs”* as well as all price-based programs (refer to Fig.1), rather than ‘*Ancillary (services)*’ as it is rarely considered. The main objective of demand response in building field is mostly to reduce or limit the electric consumption at the peak period for the economic operation of a power grid when inefficient and expensive generation is engaged. By contrast, the main target of ancillary services is to maintain the reliability operation of a power grid. To avoid the conceptual confusion, the term of “conventional demand response” is introduced here to include the demand response functions to which we usually refer in building field. This term is used in parallel with the concept of “ancillary services” that is originated from and currently used in the power grid field.

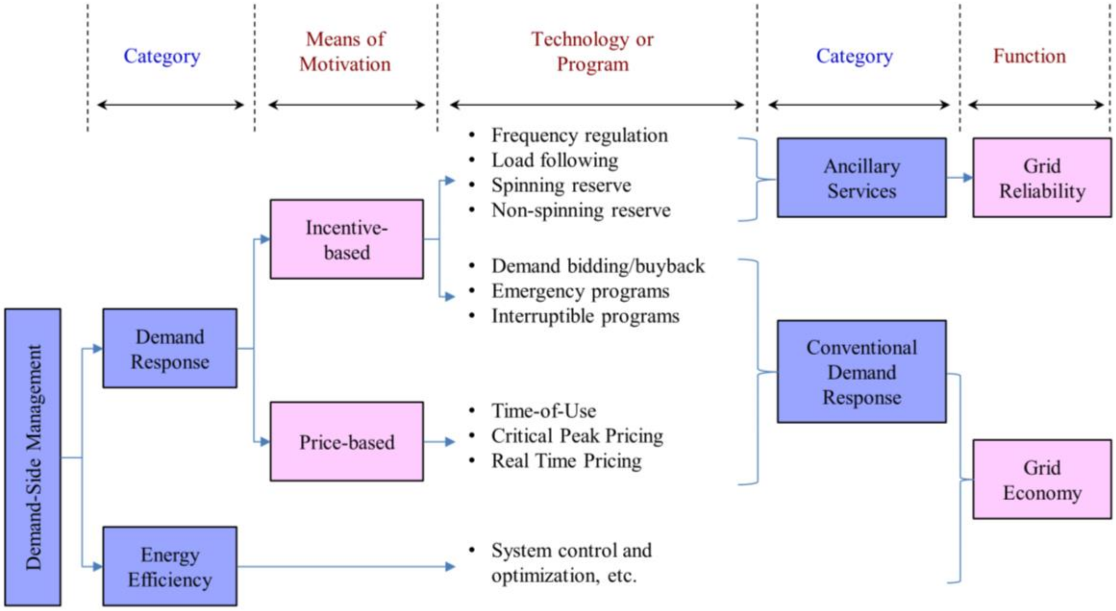

Fig.1. Categories, technologies and their functions of demand-side management

A comparison between “conventional demand response”, frequency regulation (FR) and spinning reserve is made as shown in Fig.2 to illustrate the needs and characteristics of typical ancillary services provided by demand side in normal operation and contingency operation. Among the four ancillary services provided by demand side, FR aroused more interest because of two reasons. First, it is the most expensive one [49]. Second, the required capacity of FR will increase as the consequence of increasing proportion of renewable energy generations in power grids while the required capacity of spinning reserve and non-spinning reserve in contingency condition will not be affected significantly [50]. FR also has the more distinction from “conventional demand response”. It is arising from prediction error which is normally caused by the fluctuation of intermittent power generations or variable loads. Therefore, it is technically unbiased and zero-mean over a longer time span [44]. Consequently, the demand side is required to consume less or more power than its baseline at times. However, demand side is only asked to reduce its power consumption in “conventional demand response”. Furthermore, FR is needed year-round while “conventional demand response” is normally required during peak hours [42]. Technically, a system can be used to provide “conventional demand response” and FR simultaneously because they are not contradictory.

For spinning reserve, it shares more characteristics with “conventional demand response”. As shown in Fig.2, both of them are power demand reduction within a given period at demand side. However, there are two main differences between them. First, the peak pricing period is normally informed by the supply side some hours or even a day before a demand response event when applying “conventional demand response”. This makes it possible for precooling buildings that can increase the capacity of peak load reduction. By contrast, spinning reserve is provided in a contingency situation, meaning that it can happen at any time in a day and demand side cannot be informed in advance. Second, “conventional demand response” normally lasts two to three hours, while the duration of spinning reserve is much shorter allowing significant more capacity in providing such services at demand side. Although Independent System Operators (ISOs) differ in their use of spinning reserve, it is about 10 minutes in average for deployment duration and it only very rarely requires response longer than 30 minutes [45]. Previous research has also demonstrated that the load reduction capacity is capable to provide spinning reserve that to provide "conventional demand response" for a few times [51].

Some articles introduced a new concept of "fast demand response" [32, 34, 35, 52]. The strategies proposed in these articles highlighted the response speed without notifications in advance. They can be therefore adopted for spinning reserve or for the integration of spinning reserve and non-spinning reserve when the load reduction can be fast enough and last long enough.

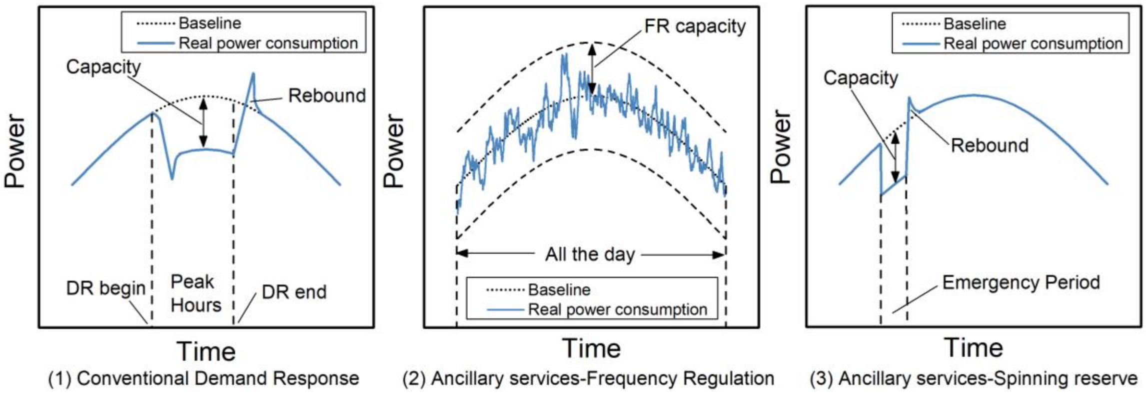

Fig.2. Schematic comparison between conventional demand response, frequency regulation and spinning reserve

3. Benefits of using HVAC systems of buildings in providing ancillary services

3.1 Benefits for demand side in providing ancillary services

Controllable and large untapped demand side is a preferable candidate to provide ancillary services with many benefits. Here the demand side refers to a broad concept, including the load of commercial buildings, residential buildings, municipal infrastructure, agriculture, data centers and warehouse [42]. Actually, the study about demand side as a resource can date back to decades ago [43] due to its obvious benefits both to grid and customers. It can improve reliability resources available to system operators and increase system flexibility to manage variability and uncertainty, so that wind and solar generation can be integrated into utility grid accordingly. Moreover, it enables retail customers to manage costs and get economic benefit in the process [42]. In addition, compared with supply side, demand side as resource has a lot of advantages: 1) demand side responds more quickly compared with most generators with ramping rate limitation; 2) the variability of power use in demand side is even larger than that of the small number of large generators in supply side; 3) the efficiency of power generation can be improved and the overall grid emissions will decrease because generators operate more efficiently with constant outputs; 4) The operation life of generators will be prolonged by alleviating wear and tear of them which normally arising when providing ancillary services [21] [23].

3.2 Benefits of using HVAC systems in non-residential buildings in providing ancillary services

HVAC systems in building sector have great advantages for providing ancillary services. The first reason is the large proportion of both energy and electricity consumption. Currently, building sector takes up 74% of electric energy in the United States [35] and about 16% of electric power is consumed by HVAC systems in residential and commercial buildings [25]. In Hong Kong, buildings consumed over 90% of the total electricity, and HVAC systems contribute about 29.8% electricity in non-residential buildings [53]. Another reason is that the internal mass of buildings is a natural thermal energy storage. For providing spinning reserve, the main sacrifice is the limited increase of indoor air temperature, while for providing frequency regulation, it is even more favorable. As mentioned above, frequency regulation arising under normal operation is attributed to forecast errors which are unbiased and zero-mean, so the indoor air temperature might not even increase except some fluctuations that allows buildings to be almost ideal candidates in providing these services [44]. Moreover, the quality of ancillary services provided by HVAC systems can be higher than other regulation resources, such as hydro, steam, combustion turbine or even battery in some conditions [54, 55].

Compared with residential buildings, non-residential buildings have some advantages in providing ancillary services. First, HVAC systems can be controlled directly to provide ancillary services using currently existing building automation systems (BAS) in non-residential buildings. That can reduce initial investment. Second, the equipment types in non-residential buildings are more favorable to provide frequency regulation. In fact, HVAC systems in non-residential buildings are often equipped with variable-frequency drives (VFDs), while HVAC systems in residential buildings are typically electric equipment with on/off control. When providing frequency regulation, frequency conversion components are more favorable since each of them can be controlled continuously to track the frequency regulation signal closely. By contrast, this service will necessitate the installation of home energy management system (HEM) in every household in residential buildings and a cooperative home energy management systems (CoHEM) as an aggregator in an area [38, 39]. Where, the CoHEM manages the modes of each component according to their current working condition and willingness to respond.

4. Studies on HVAC systems of non-residential buildings in providing ancillary services and applicable technologies

4.1 HVAC systems for frequency regulation

4.1.1 Applications of HVAC systems in frequency regulation

After the final rule of Federal Energy Regulatory Commission order NO.755 issued in 2011, more and more studies have been conducted on using HVAC systems in non-residential buildings to provide frequency regulation. Table 2 provides an overview of these studies in a chronological order up to the most updated journal publications. The components used and variables to be controlled for providing frequency regulation are listed. The validation methods and main results are summarized as well.

Table 2 Overview of research for HVAC systems in non-residential buildings to provide frequency regulation

Year	Author	Components	Control variable	Validation method	Main Results
2011	Kawachi et al. [18]	Heat Pump	Output temperature set-point	Simulation combined with a microgrid	A dynamic model of a heat pump is proposed; The capacity of energy storage system is reduced; The temperature deviation caused by load control is small.
2012-2013	Hao et al. [19, 20]	Fan	Frequency of the fan	Simulation combined with a building	15% of fan power capacity can be used for FR; Indoor temperature variation is within ±0.2 °C; 6.6GW can be provided by supply fans in existing commercial buildings, which is about 70% of the current regulation capacity required in the U.S.
2013	Maasoumy et al. [21]	Fan	Supply duct static pressure (SDSP)	Experiment	At least 4 GW of FR reserve is readily available only through commercial buildings in the U.S.; Consequent variations of the air mass flow into the building does not impact the indoor temperature in a human-noticeable way.
2013	Lin et al. [22]	Fan + Chiller	Flow mass set-point of supply air	Simulation combined with a room Validated with performance score defined by Pennsylvania–New Jersey–Maryland (PJM)	47 GW of regulation reserves is available from commercial buildings in the U.S.
2013	Zhao et al. [23]	Fan Fan + pump + chiller	(1) Static pressure set-point of the supply fan (2) Indoor temperature set-point	Simulation Validated with performance score defined by PJM	The control methods proposed can fulfill the requirement of performance score defined by PJM.
2014	Goddard et al. [56]	Fan	Global thermostat resets	Experiment on a 300 000 ft2 commercial-style office building.	A predictive model of HVAC air circulation fans is developed to provide power use flexibility by resetting the global thermostat.
2015	Lin et al. [24]	Fan	Flow mass set-point of supply air	Simulation & Experiment Validated with the	Satisfactory FR service can be provided by HVAC systems without noticeable effect on indoor temperature.

				performance score defined by PJM	
2015	Su and Norford [25, 26]	Chiller Fan + Chiller	Output temperature set-point	Experiment Validated with the performance score defined by PJM	Control strategy proposed can meet the performance requirement of PJM; Indoor climate is not affected significantly.
2015	Kim et al. [27]	Variable speed heat pump	Frequency of the heat pump	Simulation combined with a microgrid	Variable speed heat pump can be effectively exploited as the Direct Load Control enabled load; Building occupant comfort and long-term device performance can be ensured as well.
2015	Zhao et al. [9]	Fan + Chiller	Supervisor control include (1) static pressure set-point (2) indoor temperature set-point (3) discharge air temperature set-point (4) outside air fraction	Simulation Validated with the performance score defined by PJM	Large commercial buildings can provide high-quality FR service with significant FR capacity. Benefit to the power system reliability would be significant.
2016	Fabietti et al. [57]	Electric heater	Power of the electric heater	Experiment validated in the Swiss market	A model predictive control (MPC) framework is presented to assess the variation of the power use that a building can support without impacting occupants' comfort.
2016	Beil et al. [58]	Fan	Fan speed Supply pressure/mass flow Indoor temperature	Experiment validation in a 30000 m2 commercial office building	The observed aggregate scores are in the 0.5–0.65 range and fall short of the 0.75 score required for qualification. Building communication latency and mechanical latency can significantly impact the performance for frequency regulation.
2016	Kim et al. [59]	Variable speed heat pump	Output temperature set-point	Experiment validated in the lab with the performance score defined by PJM	The direct load control enabled variable speed heat pump can effectively reduce grid frequency deviations and required reserve capacities of generators.
2017	Gorecki et al. [40]	Electric heater	Power of the electric heater	Experiment validated in the Swiss market	The proposed control strategy can offer higher regulation capacity at the same fixed level of comfort.
2018	Vrettos et al. [28, 29]	Fan	Frequency of the fan	Experiment	With a hierarchical control, buildings can determine the reserve capacity and baseline power, and identify the optimal tradeoff between frequency regulation and energy efficiency.
2018	Qureshi and Jones [30]	Fan + Chiller	Indoor temperature set-point	Simulation	A hierarchical control is proposed to maximize the flexibility and provide frequency regulation services.
2019	Cai and Braun. [54, 60]	Variable-speed packaged rooftop unit and a split heat pump	Discharge air temperature	Experiment Validated with the performance score defined by PJM	The closed-loop regulation control was shown to have negligible impact on indoor comfort with temperature fluctuations smaller than 0.1 °C.
2019	Wang et al. [61]	Pump	Frequency of the pump	Simulation Validated with performance score defined by PJM	The impact to indoor air temperature is almost neglectable with the thermal capacity of the cooling coil and indoor air offsetting the fluctuation of pump frequency.
2019	Daher et al.[62]	Supply fan with the return fan	Frequency of the fans	Simulation combined with wind power generators	The proposed method reduces wind power losses and keeps the temperature variation unperceived.

4.1.2 Basic approaches for HVAC systems in providing frequency regulation

This section provides a summary on the technologies studied for using HVAC systems in providing frequency regulation, after a brief introduction on the technologies used at the supply side for the same function. As shown in Table 1, there is a combination of three mechanisms that is used in the supply side to provide ancillary services in normal operation. When a deviation of frequency occurs, the rotating inertia of all synchronous generators will activated for the primary frequency modulation. Where, the deviation cannot be fully removed. Second, the generators installed with frequency responsive governors will respond to the frequency deviation and generate an output change proportional to such deviation. In practice, these generators change their generations as soon as a frequency deviation occurred. The third mechanism is called Automatic Generation Control (AGC) which is managed by “balancing authorities” (BAs), these authorities will calculate the “area control error” (ACE) and send out an AGC signal which represents the magnitude of power imbalance between supply side and demand side [44]. The AGC signal is normally at small intervals. For example, it has the interval of 2 seconds in Pennsylvania–New Jersey–Maryland (PJM) [63]. Both supply side and demand side can receive, process and respond to the AGC signals. However, it is worth of noticing that the AGC signals received by the demand side are typically the signals reversed by some power regulation/management organizations, such as the Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs) in the US. That means that demand side is scheduled to consume less power when originally scheduled for regulation up for more power generation at supply side [64]. Similarly, demand side is scheduled to consume more power when originally scheduled for regulation down for less power generation at supply side. To fulfill such needs, the frequency response of HVAC systems in buildings at demand side could be achieved by modifying their existing control strategies (see Fig.3), allowing the systems to modulate their power uses following this signal.

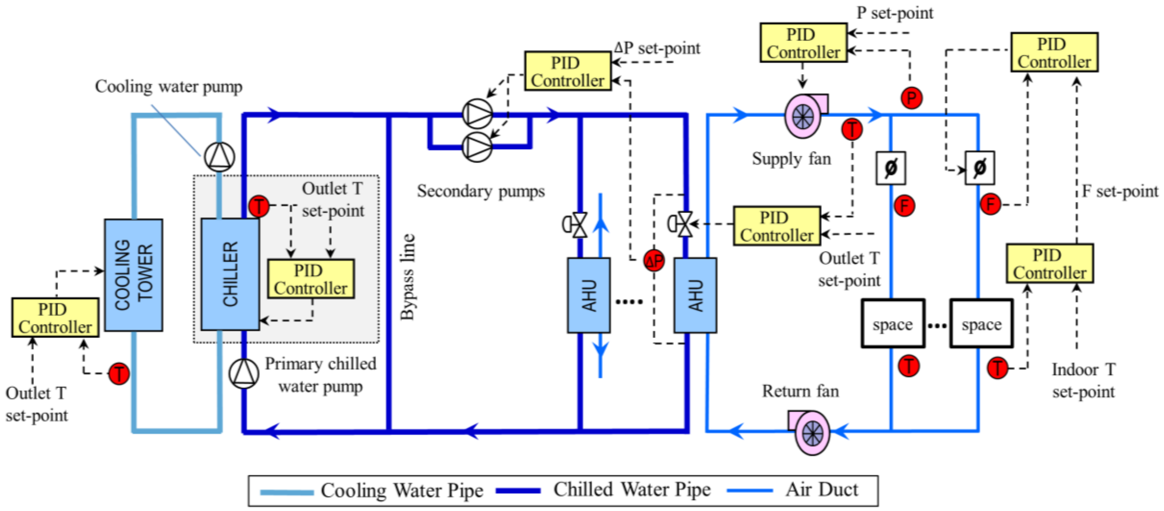

Fig.3. A typical control strategy of HVAC system in non-residential buildings

Different from HVAC systems in residential buildings, the systems in non-residential buildings have more complex integrated sub-systems which involving diverse electricity-consuming equipment and interdependent control loops that create self-correcting behavior [58]. So a better understanding of the typical operation and control strategy of HVAC systems in non-residential buildings is needed before investigating the regulation control on a higher level. Fig.3 shows a typical control arrangement of a variable air volume (VAV) system. In the air-side control, the space temperature is measured and the temperature controller resets airflow rate (F) set-point by comparing the measure spaced temperature with its set-point. Similarly, by comparing the measured airflow rate with its set-point, the airflow controllers modulate the openings of the air dampers to control the (measured) airflow rates at their corresponding set-points. The supply fan speed is typically modulated to maintain the static pressure of air in the supply duct at its pressure set-point. At the water side, the chilled water flowrate through an air-handling unit (AHU) is controlled by modulating the valve opening to control the supply air temperature at its set-point. The pump controller is responsible for maintaining the differential pressure between the supply and return pipelines (typically across the most remote AHU) at its set-point by controlling the proper number operating pumps and their speed. The cooling tower controller maintains the tower outlet water temperature at its set-point by controlling the number and modulating the speed of operating towers. The control panel of each chiller also controls the outlet chilled water temperature at its set-point.

Based on the studies listed in Table 2, the mechanism of typical control strategies of HVAC systems for providing frequency regulation services to utility grids can be summarized and illustrated in Fig.4. Where, the energy component could be any controllable power user, such as a fan, pump or chiller. X is the controlled output variable that is measured and regulated. It can be observed that the system control for providing frequency regulation services is achieved by modifying existing control strategies of HVAC systems. In the system control for frequency regulation, the local process or component feedback controls are the same as that in their normal system operation (i.e., that shown in Fig.3). To control the power use of a component for providing frequency regulation, a regulation controller is designed as a core element on top of the normal control, which operates as described in the following.

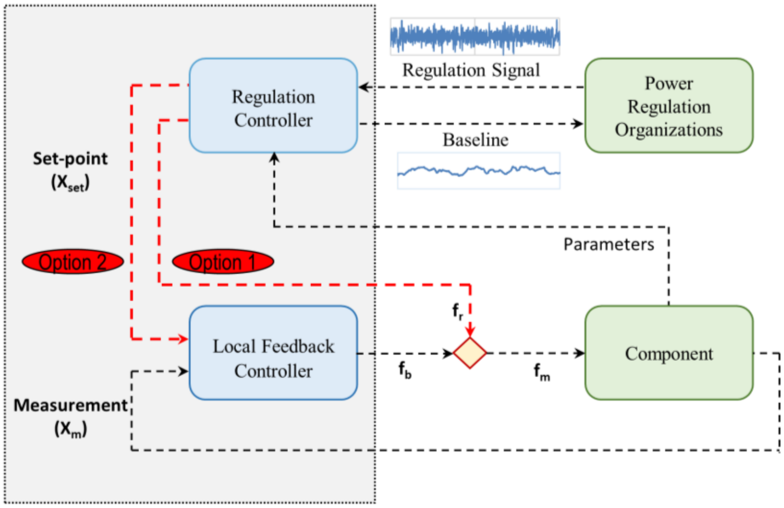

Fig.4. Typical control strategy for HVAC system to provide frequency regulation

When receiving the frequency regulation signal from the power regulation/management organization concerned, the regulation controller modifies the power use of the component by modifying the normal frequency control either by Option 1, adding an extra signal f_r directly on the normal frequency control signal f_b, or by Option 2, resetting the set-point (X_{set}) of the frequency controller consequently interfering frequency control signal f_b indirectly, according to the AGC signal (as well as the agreed regulation capacity). In fact, adding an extra signal directly allows quick response to the frequency regulation signal, however low frequency variations of the regulation signal f_r are not desirable since the local feedback controller will offset the f_r, being considered as a noise [65]. By contrast, resetting set-point X_{set} allows to lower frequency interfere to be added into the process control, however it will take longer time for the system or the local feedback controller to response to the frequency regulation signal. For example, it will take more time to change the power use of a chiller by resetting its outlet temperature set-point compared to adjusting its frequency directly.

Another basic function of the regulation controller is to send the baseline of this component back to the power grid, which refers to the power use of the component without adopting frequency regulation. This baseline value is needed and utilized by the power regulation/management organization concerned for power demand prediction. It is typically acquired from the current but "interfered operation state" of the component which is then be processed to get the "true operation state" without adopting frequency regulation.

Another application scenario is micro-grid in which frequency control is an essential issue because of the large proportion of renewable electricity generations. In a micro-grid, the regulation controllers will normally monitor the frequency of the power grid themselves in real-time (rather than receiving frequency regulation signals from the power grid) and respond simultaneously to remove the frequency deviation [18, 27].

4.2 HVAC systems for spinning reserve

HVAC systems have been also considered to provide spinning reserve in the power grid. Table.3 presents a summary on the applications of HVAC systems in non-residential buildings for spinning reserve. In such applications, the control strategies are similar to that in "conventional demand response", while not all the strategies are suitable for the case of spinning reserve due to its response speed requirement. By simulation, Blum and Norford [33] have proved that many control strategies (i.e., that shown in Table.3) of HVAC systems could meet the response speed requirement of spinning reserve. For experiment, zone air dry-bulb temperature set-point reset is qualified for non-spinning reserve [66, 67]. In practice, the most common approach is still shutting down equipment directly for a fast response. In [31], the full response only required 12 to 60 seconds after the system operator's command to shed load was issued. With the outdoor temperature at 32.2℃, the average temperature increased 0.95℃ and humidity rose 2 percent during the 15-minute test.

Table 3 Overview of research for HVAC systems in non-residential buildings to provide spinning reserve

Year	Author	Components	Control method	Validation method	Main Results
2008	Kirby et al. [31]	Air conditioning unit	Shutting down	Experiment	Full response occurred in 12 to 60 seconds. The load can be curtailed by 22 to 37 percent depending on the outdoor temperature and time of the day.
2014	Nikolic et al. [32]	Air conditioning unit	Shutting down	Experiment	Spinning reserve can be dispatched and confirmed within 1 second. The technology has been installed tested in an Isolated power system in Australia.
2014	Blum and Norford [33]	Chiller Fan	Adjustment of (1) zone air dry-bulb temperature (2) duct static pressure (3) supply air temperature (4) chilled water temperature	Simulation	The proposed methods are validated, with all of them meeting the requirement of reducing power consumption in 10 minutes.
2016-2017	Wang and Tang [34, 35]	Chiller	Shutting down	Simulation	The problem (uneven indoor air temperature rises) resulting from shutting chillers is properly solved by proposed control strategy.

2017	Mega et al. [36]	Air conditioning unit	Shutting down	Experiment	It is possible to reduce energy consumption by more than 10% by controlling the air conditioning.
2018	Tang et al. [37]	Chiller	Shutting down	Simulation	Expected power reduction (i.e., about 23%) is achieved and acceptable zone temperature is maintained even though uncertainties exist in the prediction process.

5. Challenges for HVAC systems in providing ancillary services and proposed solutions

5.1. Challenges and limitations when providing frequency regulation

A few challenges and limitations are encountered when using HVAC systems for frequency regulation. They are mainly due to the characteristics of the component contributing for frequency regulation (such as limitation operation regime, time constant), the impacts of the component on other associated components and built environment control, and the impacts on the control stability/energy efficiencies.

5.1.1 Limitation of component characteristics

Components activated can contribute limited percentage of rated or operating power for frequency regulation only, due to different constrictions. According to previous studies, for providing frequency regulation, the acceptable lower limits of actual running powers for different chillers are between 33% to 50% of their rated powers [26] while a fan can provide regulation capacity of about 15% of its operating power under the working conditions studied [19, 20]. More detailed factors due to characteristics of components themselves, which affect the capacities and performance in providing frequency regulation, are summarized as follows in this section.

Limitation of component operation regime: Operation regime is an inherent limitation for HVAC components to make their full use of their capacities in providing frequency regulation. For instance, there are three distinct operation mechanisms for centrifugal chillers to change power use which is originally designed for capacity control, including inlet vane control, variable frequency drive (VFD) and hot gas bypass. When reducing the cooling output from the full capacity of the chiller, the compressor speed will be decreased by using VFD. However, it is typically only decreased down to about 60% of the design speed [68]. To further reduce the cooling output, the chiller would then change the refrigerant volume flow rate through the centrifugal compressor by controlling the inlet vane [69]. At the lowest capacity lever, for example, 10% of design capacity [70], the hot gas bypass is finally utilized to reduce the cooling output. Normally, it is inefficient because it has a quite limited influence on power use and should be avoided when providing frequency regulation. Moreover, the outlet temperature set-point of a chiller (which is normally used to adjust its power use for demand response) has specific range. This range can cause saturation when providing frequency regulation which can limit the ramping rate [25].

When the chiller has multiple compressors, it will encounter another implication called "cycling" when providing frequency regulation by frequently resetting its output temperature set-point. Here, cycling refers to frequently adding and dropping of compressors. It can jeopardize frequency regulation quality/stability significantly and thus constricting frequency regulation capacity or the use for frequency regulation. One possible solution is to predict the threshold of cycling and then to avoid it. However, that is quite difficult in practice because it may operate without cycling or cycling continually even under similar cooling requirement condition [26]. Another possible approach is to adjust the internal control parameters of the chiller to make it more favorable for providing frequency regulation, while it might be unfavorable to its original operating efficiency. The conflict between energy efficiency and ancillary services will be investigated in a later section.

Simpler than chiller, the speeds of fans and pumps are controlled solely by their VFDs. In applications, attention should be paid that motors are not allowed to operate below their minimum speeds which is subject to their technical specifications. Normally, belt-driven fans should not operate below 10% of their full speeds to avoid insufficient motor cooling, while typical gear-driven systems can operate at as low as 25% of their full speeds to meet their lubrication requirements. Regarding external oil pumps which are installed in the gearbox for constant lubrication, the minimum speed is 10% of their full speed, being confined by cooling limitation as well [71]. Except the minimum frequency limitation of the fans and pumps, another problem is the schedule of baseline frequency f_b. As mentioned above, the frequency of a fan or pump is controlled by adding an extra signal produced by frequency regulation controller on the top of its baseline frequency. So when this baseline frequency is close to its upper (or lower) limit frequency under a high (or low) cooling load condition, the adjustable range for frequency regulation will be highly restricted undoubtedly. Moreover, motor speed ramp-rate limiters in the VFD may also restrict the highest response frequency [58].

<u>*Time constant of response:*</u> The time constant of a component is a factor which can be used to evaluate the response speed to frequency regulation control. It has a great influence on performance scores, especially the delay score. This score is applied for evaluating the performance of frequency regulation service by PJM standard, and the other two scores are precision score and correlation score respectively [63]. The chillers/heat pumps, whose frequency can be changed directly, have been demonstrated by simulation that they are qualified to provide frequency regulation [27]. However, it is not capable for most of the chillers/heat pumps installed in the existing buildings. As a result, many researchers have also investigated their abilities by resetting their outlet temperature which have larger time constants obviously. As reported by Su and Norford [26], the time constant observed in the compressor speed regime is about 30 seconds to 1 minute when continually resetting the chiller output temperature set-point for frequency regulation. For chillers/heat pumps of small capacity that serve residential buildings, an experiment study has proved that they can provide high-quality frequency regulation [54, 60]. However, for non-residential buildings installed with large capacity chillers, for example, in the experimental study conducted by Su and Norford [26], 7 out of the 9 tests could not meet the performance score requirement of PJM. Such large time constant can be explained by its ramp-rate limitation decided by parameters of PID loops in the onboard control logic of chillers, which are originally designed for stable operation. Although they could be adjusted in the factory, it may arouse other issues like energy-efficient loss or higher requirement of mechanical strength. Compared with chillers, fans and pumps normally have smaller time constants, typically in seconds, due to their lower inertia. As a result, they can respond faster and more accurate than a chiller and can thus get a higher PJM performance scores. In summary, chillers are more favorable for responding to low frequency regulation signals (i.e., RegA, the low filter ACE signal sent out by PJM [63]) while pumps and fans can respond to higher frequency regulation signals (i.e., RegD, the high filter ACE signal sent out by PJM [63]). Moreover, communication delay in actual buildings can significantly increase the time constant of response. In the experimental study conducted by Beil et al. [58], the fans were adopted for frequency regulation. However. the performance score is much lower than that got from another simulation study [23] with the same control strategy.

5.1.2 Effects on environment control and other associated components

HVAC systems are complicated systems in which all the components/subsystems are thermally or hydraulically correlated. Any change of a controlled variable will naturally affect the power use of other components in a system and the performance of the entire HVAC system. Here, we consider this kind of change as “side-effects” when providing frequency regulation as the objective. Normally, there are two main types of side-effects. (1) Indoor temperature variation which might eventually constrain the capacity of frequency regulation when such variation is beyond an acceptable range; (2) Power use variations of associated devices which may enhance or suppress the contribution of frequency regulation service when taking the HVAC system as a whole.

When adopting a fan at the air-side to provide frequency regulation, it is expected that it may have direct effect on the indoor air temperature because it usually affects directly on the flowrate of the cooling/heating air to the indoor space without intermediate system between them to offset the variations. As reported by Hao [19, 20], the indoor temperature deviation is about ±0.2◦C for fans to provide 15% of their rated power for frequency regulation. Adjustment of fan speed will also cause the power variations of associated chillers and even the associated pumps in a variable-volume system usually. The quantitative side-effect of a fan speed change to associated chillers is affected by many factors, including regulation capacity provided by the fan, “energy content” and the time constant of the chillers. Here, “energy content” [28] refers the accumulated value of an AGC signal above (or below) its baseline. For example, RegA has a larger energy content than RegD. Normally, the quantitative side-effect of a fan speed change to associated chillers has a positive correlation with the regulation capacity and energy content while it has a negative correlation with the time constant of chillers. Based on the experiment results, Vrettos and Kara [28, 29] concluded that fan speed control can provide frequency regulation with negligible side-effect on chiller power use. It is worth of noticing that there are many favorable preconditions in their experiment studies, including the choosing of a relatively small energy content signal (RegD) and a chiller integrated with a water storage tank which enlarges chiller time constant significantly. In a simulation study involving one chiller and four fans, the power use variation of the chiller was also considered when adopting these fans for frequency regulation [72]. The results prove that this side-effect needs to be taken into consideration. Similarly, in an experimental study, a nonnegligible impact on the chiller power use was also found when using fans for ancillary services [73].

When adopting a chiller to provide frequency regulation, the variations of chiller power input will result in the fluctuation of the chiller outlet temperature and further cause the above-mentioned two types of side-effects in principle. However, as reported in previous studies [18, 25, 26], no noticeable impact on indoor temperature is observed practically when providing frequency regulation. A possible explanation for this might be the existance of some intermediate loops between chillers and air-conditioned indoor spaces, i.e., a water circulation loop and an air circulation loop, which can effectively alleviate the impact of the chiller output temperature variations to the indoor temperature. Meanwhile, in variable volume systems, it might also cause the side-effect of power variations in associated devices, such as variations of pump or/and fan powers due to the adjustments of their speeds. Experiment research on such correlations is quite rare. An related reference reported a study on a system with a variable chilled water loop, a constant condenser water loop and a cooling tower with a variable-speed fan [26]. The experimental data show that flow rate variation of chilled water and ΔT at the chiller condenser were about ±5% and ±20% respectively when the chiller was providing 25% of its rated power for frequency regulation while space temperature was not affected noticeably.

5.1.3 Conflict between ancillary services and control stability/energy efficiency of systems

System/process control stability is one of the major performance objectives in practical operation. However, when providing frequency regulation, the speeds of selected components should be controlled to follow the AGC signal that injects an artificial disturbance continuously. Moreover, as mentioned above, HVAC systems are complex systems in which all the components/subsystems are thermally or hydraulically correlated. As a result, it is a serious challenge for HVAC systems to maintain the system/process control stability when providing frequency regulation, especially when a frequency regulation of large capacity is provided.

System energy efficiency is another major performance objective in practical operation. In the experimental study of Beil et al [58, 74], the results indicate that HVAC systems can consume more energy for providing frequency regulation than when its normally operation. The results in another experimental study of Keskar et al.[73] is consistent with the result of Beil et al [58, 74], showing that the Up-down power variations are more efficient than Down-Up power variations.

Similarly, the result observed in the study of Raman and Barooah [75] indicate that when the HVAC system's power consumption was increased and decreased continuously, there was on average a slight warming of the building even though the temperature variation was within a certain range. In a further study conducted by Lin et al. [76], it has also demonstrated that the power consumption of the components for providing frequency regulation can be significantly affected. Some factors that affect the efficiency loss include the average temperature during the event and the temperature at the end of the event, the sequence of the signal (i.e increase at first of decrease at first), the characteristic of the regulation controller and energy content. The impacts on this efficiency loss by other factors, such as building size and time period of power deviation, were discussed in the study of Raman and Barooah [77]. Another conflict between frequency regulation and energy efficiency of systems might happen when a component has to reschedule its baseline frequency in a suboptimal way to spare sufficient capacity for frequency regulation. As reported by Vrettos et al. [29], this efficiency lose was as high as 67% when compared with an efficient control without providing frequency regulation in his experimental study where a fan is used to provide this service. In the study of Blum et al. [78], an optimization method was proposed to minimize the total operation cost considering the cost of energy and the revenue from providing ancillary services with the constraints of zone temperature and system operation regime. To balance the tradeoff between energy efficiency and frequency regulation for the greatest benefit for buildings and grids, further research is needed. In their further study [79], they proposed a definition for the costs of HVAC in providing ancillary services and quantified them by recognizing the impacts on daily energy efficiency and costs associated with ancillary service provision.

5.2 Challenges when providing spinning reserve

Similar to the existence of challenges when providing frequency regulation, use of HVAC system to provide spinning reserve will also encounter different challenges. The major challenges are the uneven cooling distribution and rebound effect as elaborated below.

5.2.1 Effects on environment control and other associated subsystems

Shutting down part of operating devices directly, as a fast demand response method, is an effective means for HAVC systems in non-residential buildings to provide spinning reserve [34, 35, 80]. As shown earlier in Fig.3, typical control strategies for air-conditioning systems in buildings are demand-based feedback control, which is based on a basic assumption that users at the demand side can get as much as they need from supply side. However, after shutting down some operating devices (such as chillers) for providing spinning reserve, the sudden substantial undersupply will result in the sacrifice of environment control, such as indoor temperature increase, particularly when the period of services is getting longer. The uneven cooling distribution at both water side and air side is another challenge due to the fact that all users at demand side will compete for the limited supply while the "competitiveness" are rather different. This will in turn worsen the sacrifice of environment control in the spaces which are at disadvantaged positions when competing for limited cooling supply [35].

Another challenge is the side-effects on other associated subsystems, which also result from the substantial cooling undersupply. To get adequate cooling and maintain the space temperatures and outlet air temperature of AHUs at their set-points, the corresponding feedback controllers will open valves and dampers until fully open position. The controllers of associated subsystems/devices, such as secondary pumps and AHU supply fans, would speed up them, even to full speed, to maintain the controlled differential pressures at their set-points. This will eventually end up with significantly increased power uses and offset the power reduction of shutting down operating chillers [35].

5.2.2 Rebound effect

After a spinning reserve service, devices are resumed to provide normal services, such as providing cooling supply as demanded. However, because of the increased indoor air temperature, the cooling demand usually will be higher than the normal value which results in a significantly higher power demand/use for a period of time. This phenomenon is regarded as "rebound effect" [41]. Actually, it also happens in "conventional demand response" [81].

5.3 Advanced control strategies and promising solutions

In recent years, some efforts on control strategy have been made to cope with the challenges raising from providing ancillary services by HVAC systems. Some regulation controllers are designed with hierarchical control architecture in which different regulation functions are realized by multiple interacting levels as the example shown in Fig.4. The following schemes in literature were proposed with the objective to solve the problems raising from providing frequency regulation. A "contractual framework" was proposed by Maasoumy et al, based on robust MPC, to quantify the regulation capacity of a signal commercial building which can maximize the reward and declare this regulation capacity to the utility [82]. After the previous simulation studies conducted in 2014 [83] and 2016 [84], Vrettos et al. [28, 29] proposed a hierarchical controller with three levels and validated it by experiment in 2018. The basic level of the controller was designed for tracking the frequency regulation signal by modifying the fan power via fan speed control with a VFD. The task of its middle level is to calculate the supply air flow rate set-points that compromise energy consumption and indoor air temperature. The highest level of the controller is responsible to determine the reserved capacity that can be provided for frequency regulation. In the study of Qureshi and Jones [30], the temperature set-points of the controllers at the lowest level are determined by the higher level controller which has the objective to maximize the flexibility of building thermal energy use. At the highest level, an electrical flexibility controller controls the HVAC system to maximize the flexibility of power use. Fabietti et al. [57] presented the design of two MPC based controllers to quantify the flexibility of a commercial building to solve the bidding problem. Later on, the proposed method was validated by experiment in the electricity market of Switzerland. Gorecki et al. [40] also proposed a multiple layers control strategy. The basic layer has the similar fundamental function to modulate the power use of electric heaters to provide the frequency regulation. A higher layer adopting Model Predictive Control (MPC) determines power use baseline and the optimal value of system power use. The highest layer, namely reserve scheduler, commits the capacity bid for the next day.

Another architecture for controllers is to integrate multiple components rather than one component. In this way, the coordination between different components can be incorporated in the controller, and the side-effect, power variation in associated devices, can thus be handled. In the study of Lin et al. [22] , the total power use of fans and chillers were taken as a whole for providing frequency regulation by modulating the supply airflow set-point. In the study of Zhao et al. [23], the power use of all HAVC components was also considered as a whole when providing frequency regulation by resetting the supply fan static pressure set-point and the indoor temperature set-point.

A supply-based feedback control was proposed by Wang and Tang to solve the problem of uneven cooling distribution when providing spinning reserve by fast demand response [35]. In their study, global and local cooling distributors are introduced based on adaptive utility function. By resetting the set-points of chilled water flow and air flow for each zone and space, this strategy can maintain even indoor air temperature rises during spinning reserve event. For rebound effect, several solutions have been proposed in publications related to “conventional demand response”, including a slow recovery strategy [41], sequential equipment recovery [41, 85], and demand response control period extention [41].

6. Quantification of ancillary services potentials provided by HVAC systems in buildings

Besides the technical problems/challenges need to be addressed, it is also very important for users/decision-makers to have an overall picture on the potential capacities of buildings to provide ancillary services. This helps to have a better understanding of the economic values of potential resources for ancillary services. In this section, the potential capacities of two specific types of ancillary services (i.e. frequency regulation and spinning reserve) are quantified. These two types of services are selected for assessment as they serve normal operation and contingency operation respectively. The potential capacities provided by the HVAC systems of all non-residential buildings in Hong Kong are quantified, which are also used, as an example, to assess potential contributions to capacities of ancillary services needed. As mentioned earlier, the mechanisms of these two types of ancillary services are quite different, so different methods are adopted to evaluate each of them as elaborated in the following.

6.1 Frequency regulation

A few efforts have been made to evaluate frequency regulation capacity. Some of them were conducted for a single building [60, 82, 86] or an aggregation of buildings [83, 87] to solve the bidding problem ahead of a day or ahead of an hour. Other studies were made to investigate the overall regulation capacity of buildings in a region. In the study of Ma et al. [42], the frequency regulation capacities of different kinds of loads are estimated by filtering the load profiles with three aspects: sheddability, controllability and acceptability. In the studies reported in [19-22], the frequency regulation potential is estimated by quantifying the services capacity of the HVAC system on one particular area selected, supplemented by assuming same services capacity per unit area in all buildings in a country (selected results are included in Table 2). However, it is hard to find any study addressing the frequency regulation potentials of HVAC systems in non-residential buildings using more practical load profiles and building/system data and considering the variation of building load profiles.

In this study, a quantification method is developed based on revising the method proposed by Ma et al. [42]. The method and the reference data to use the method for the qualification of the potential frequency regulation capacities of non-residential buildings in Hong Kong are presented in the following.

6.1.1 Monthly variation of frequency regulation capacity

The required capacity of frequency regulation reserve is estimated by an empirical equation, as shown in Eq. (1) [42, 43]. Where, $C_{FR,r,m}$ is the average frequency regulation capacity required in a month. $E_{HK,m}$ is the total power consumption of Hong Kong in a month. dm is the number of days in a month. In this study, variable speed fans of AHUs are considered as the resources for providing frequency regulation.Their potential frequency regulation capacity is estimated by another equation, as shown in Eq.(2). Where, $C_{FR,p,m}$ is the average frequency regulation capacity which can be provided in a month. $E_{nr,HVAC,m}$ is the monthly power consumption of all HVAC systems in non-residential buildings in Hong Kong. α is the proportion of non-residential buildings using VFDs for AHUs. β_m is the monthly average proportion of AHU fans power use in HVAC systems. γ is the acceptable proportion of AHU fan power use as the capacity for frequency regulation. Since α is not available in Hong Kong, the value in the USA is applied for reference, 33% [19]. Moreover, two other proportions are also used in the assessment, including one more conservative estimate (α = 20%) and one more aggressive estimate (α = 50%). β_m varies in different months, the values are estimated by simulating a typical building over a typical year using TRNSYS [88]. The results are shown in Table 4. The annual average β_m obtained is 35%, which is reasonable when compared with that in Australia (i.e., 34% [89]), in Singapore (i.e., 50% [90]) and in Beijing (i.e., 45.3% [91]) respectively.

Table 4 β_m of a typical non-residential building in Hong Kong in different months

Month	1	2	3	4	5	6	7	8	9	10	11	12
β_m	0.42	0.42	0.38	0.33	0.29	0.27	0.34	0.33	0.33	0.34	0.39	0.42

According to the experimental results reported by Hao et al. [20], the fan could provide 15% of its rate power when it was working near its full speed, while the indoor temperature varied more significantly when it was working at 60% of its full speed to provide the same capacity of frequency regulation. To compromise the indoor temperature variation and frequency regulation services, γ is chosen to be 15%, which refers to the situation where AHU fans provide 15% of their current power use for frequency regulation.

Assuming that the overall power consumption in non-residential buildings except that for HVAC systems ($E_{nr,nHVAC,m}$) is constant in different months, the monthly power consumption of HVAC systems in non-residential buildings ($E_{nr,HVAC,m}$) can be estimated by solving Eq.(3) and Eq.(4). Where, $E_{nr,m}$ is the monthly total power consumption of all non-residential buildings in Hong Kong. The proportion of overall HVAC power consumption in non-residential buildings (ω) is 29.8% in Hong Kong in 2017 [53]. The values of $C_{FR,r,m}$ and $C_{FR,p,m}$ can be then computed as shown in Fig.5. It is worth noting that the monthly average values of different months over a year are presented to show their seasonal variations. In practice, both required and available frequency regulation capacities vary significantly in different days of a month and in different hours of a day.

$$C_{FR,r,m} = \frac{E_{HK,m}}{dm \times 24 \times 3600} \times 1\% \tag{1}$$

$$C_{FR,p,m} = \frac{E_{nr,HVAC,m}}{dm \times 24 \times 3600} \times \alpha \times \beta_m \times \gamma \tag{2}$$

$$E_{nr,nHVAC,m} = \sum E_{nr,m} \times \frac{1-\omega}{12} \tag{3}$$

$$E_{nr,HVAC,m} = E_{nr,m} - E_{nr,nHVAC,m} \tag{4}$$

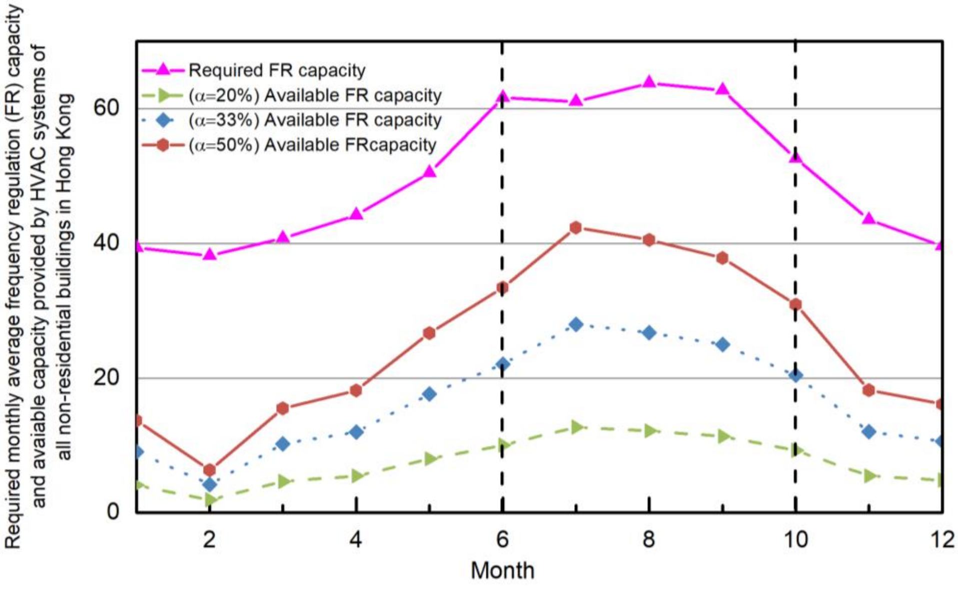

Fig.5. Required monthly average frequency regulation (FR) capacity and available capacity provided by HVAC systems of all non-residential buildings in Hong Kong

From Fig.5, it can be observed that the potential frequency regulation capacity of HVAC systems in non-residential buildings, even when only the AHU fans are considered, is rather remarkable. In the period between June and October, the potentially available FR capacities provided ($\alpha = 33\%$) can contribute almost half of the frequency regulation capacity needed in Hong Kong. However, the capacity decreases gradually after October although β_m is higher in winter, which is resulted from the decreased power use of HVAC systems in the winter season. It can be seen that, different from other frequency regulation resources, HVAC systems show obvious obseasonal characteristics. It is also worth noting that only AHU fans are considered in the above estimation and the potentially available frequency regulation capacity of the entire HVAC systems should be much more substantial.

6.1.2 Hourly variation of frequency regulation capacity

In this section, the hourly frequency regulation capacity is estimated to illustrate its variation in a day. The field power measurements of the HVAC systems in the International Commerce Centre of Hong Kong are collected and used to represent the power use characteristics of non-residential buildings. The calculation method is similar to the monthly estimation, as shown in Eq. (5). Where, $C_{FR,p,h}$ is the average frequency regulation capacity that can be provided in an hour. $E_{nr,HVAC,h}$ is the overall hourly power consumption of HVAC systems in non-residential buildings of Hong Kong. β_h is the hourly average proportion of AHU fan power use in all the HVAC systems in Hong Kong. This equation is further expressed as Eq. (6). Where, $E_{bui,Fan,h}$ is the hourly power consumption of AHU fans in the International Commerce Centre. $E_{bui,h}$ is the hourly power consumption of the whole building. The variation of $C_{FR,p,h}$ is shown in Fig.6.

$$C_{FR,p,h} = \frac{E_{nr,HVAC,h}}{3600} \times \alpha \times \beta_{\hbar} \times \gamma \tag{5}$$

$$C_{FR,p,h} = \frac{E_{bui,Fan,h}}{3600} \times \frac{E_{nr,m}}{dm} \times \frac{1}{\sum E_{bui,h}} \times \alpha \times \gamma \tag{6}$$

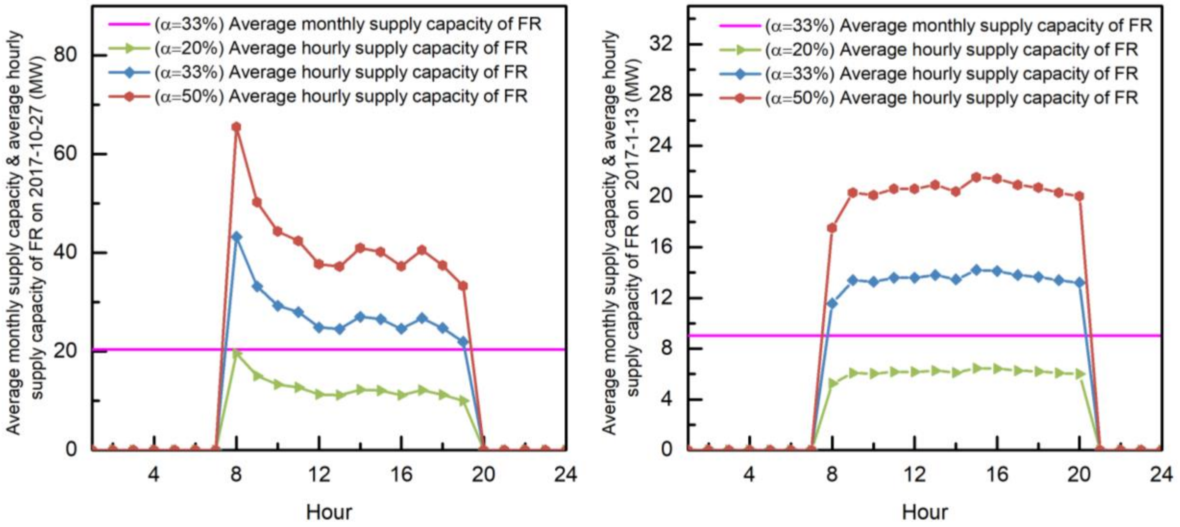

Fig.6. Monthly frequency regulation capacities and hourly frequency regulation capacities provided by HVAC systems of all non-residential buildings in Hong Kong on 27/10/2017 and 13/01/2017

As shown in Fig.6, the pink lines represent the monthly average frequency regulation capacity $C_{FR,p,m}$ ($\alpha = 33\%$) provided by HVAC systems of non-residential buildings while the other lines are $C_{FR,p,h}$ corresponding to different proportions that can be regulated. As expected, the average value of frequency regulation capacity on 27/Oct was much higher than that on 13/Jan. It can also be observed that the potential of frequency regulation fluctuates significantly throughout the day. The peak value appeared in the morning of 27/Oct, that is due to the full load operation of fans in the morning start period to remove the heat accumulated over the previous night. On 13/Jan, while the outdoor temperature was lower (maximum temperature: 15.7℃), the HVAC system might be mainly used for ventilation and the power consumption of the fans did not change much in the office hours. Comparing Fig.5 and Fig.6, it can be found that, in favorable months (i.e. from June to Oct), the frequency regulation capacity fluctuates significantly in office hours, while in other months, the frequency regulation capacity is low and the frequency regulation capacity turns out to be smoother in office hours.

6.2 Spinning Reserve

The quantification method for the spinning reserve capacity of HVAC systems is similar to that for the capacity of “conventional demand response” rather than that for frequency regulation capacity. Because the potential of HVAC systems for both spinning reserve and “conventional demand response” depend on the amount of HVAC system power reduction within the given period subject to the limit of allowed temperature rise. In the literature, many reported efforts can be found to quantify the potentials of buildings for providing “conventional demand response”[92]. In the studies of Olivieri [93] and Yin [94], different kinds of buildings are simulated by Energyplus to estimate their potentials for “conventional demand response”. In some other studies, buildings [95] and various thermostatically-controlled loads (TCLs) [96, 97] are simulated by resistance-capacity (RC) models to quantify their power flexibility when responding to smart grids. Although, from the technological point of view, it has demonstrated that aggregation of small loads in demand side is feasible for providing spinning reserves [31, 45, 98-100], there has been little quantitative analysis about its potential capacity for reference.

In this section, the potential spinning reserve capacity of HVAC systems in all non-residential buildings in Hong Kong is estimated. The detailed mechanism as well as the model used are described briefly as following.

6.2.1 Method to quantify spinning reserve provided by HVAC systems

The method proposed is based on the assumption that power use of HVAC systems can be reduced by certain amount as expected without considering specific strategies used, such as shutting down devices directly and resetting indoor temperature set-point. The capacity of spinning reserve provided by HVAC systems is their power use reduction subject to permitted indoor temperature rise (ΔT) within spinning reserve duration (t).

6.2.2 Building thermal storage model

To simulate the indoor temperature variation after reducing cooling supply, a building energy model (gray box model) [95, 101] is employed, as shown in Eq. (7).

$$Q = \sum_{i=1}^{n}\left[\frac{T_{ei,4}(t)-T_{in}(t)}{R_{ei,5}}A_{ei}\right] + \frac{T_{rf,4}(t)-T_{in}(t)}{R_{rf,5}}A_{rf} + \frac{T_{im,2}(t)-T_{in}(t)}{R_{im,2}}A_{im} + \frac{T_{out}(t)-T_{in}(t)}{R_{win}}A_{win} - C_{in}\times\frac{dT_{in}(t)}{dt} + \left(Q_{conv}+Q_{fr}+Q_{la}\right) \tag{7}$$

where, T and Q are the temperature and cooling supply of a building respectively. R and C are thermal resistance and thermal capacitance of the building respectively. A is the effective surface area involved in each specific heat exchange process. Fig.7 illustrates the configuration of the building energy model for a typical building. In this model, a building is divided into two parts:

building envelope (including external walls, roof, and windows, etc.) and building internal masses (including internal walls, floors, ceilings, partitions, and furniture, etc.). The indoor space of the building is considered as a single zone and the indoor air is assumed to be well mixed. To simplify the model, a lumped thermal mass is introduced similar to that used in [95]. As shown in Fig.8, the internal and external mass is assumed to be homogeneous and simplified as lumped internal mass and external mass respectively. Two differential equations, Eq. (8) and Eq. (9), are established according to energy balances shown in Fig.8. By solving them simultaneously on MATLAB, T_{in} can by expressed as the function of cooling supply Q and time t, shown in Eq. (10). Then the cooling supply reduction, ΔQ, can be described as Eq. (11). In this way, the potential capacity provided by HVAC systems in a certain building ($C_{SR,bui}$) is eventually expressed as Eq. (12). Where, COP_{sys} is considered as constant. The potential capacity of entire non-residential buildings ($C_{SR,nr}$) in Hong Kong can be eventually estimated assuming that the same proportion can be provided by all non-residential buildings, shown in Eq. (13).

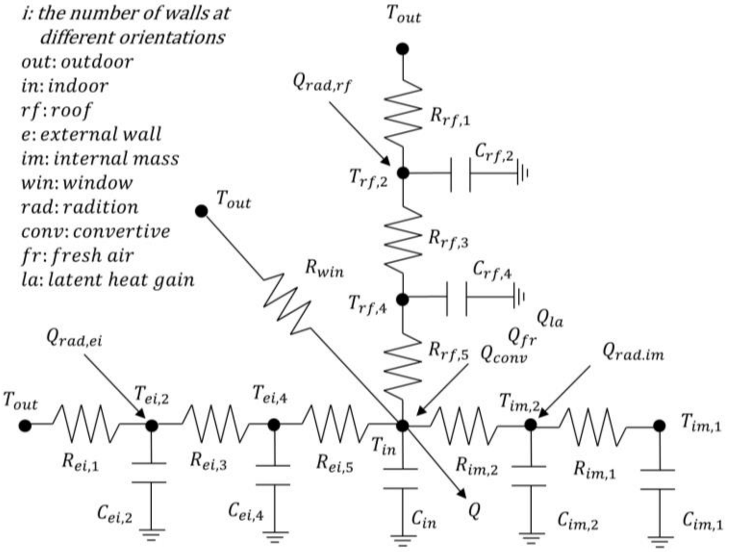

Fig.7. Configuration of the building energy balance model of a typical building

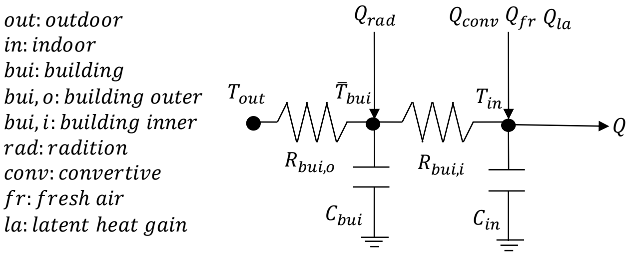

Fig.8. Building thermal storage model for spinning reserve capacity evaluation

$$C_{in}\frac{dT_{in}}{dt} = \left(Q_{conv} + Q_{fr} + Q_{la} - Q\right) + \frac{\bar{T}_{bui} - T_{in}}{R_{bui,i}} \times A_{bui} \tag{8}$$

$$C_{bui}\frac{dT_{bui}}{dt} = Q_{rad} + \frac{T_{out} - \bar{T}_{bui}}{R_{bui,o}} - \frac{\bar{T}_{bui} - T_{in}}{R_{bui,i}} \tag{9}$$

$$T_{in} = f(Q, t) \tag{10}$$

$$\Delta Q = f^{-1}(T_{in}, t) - f^{-1}(T_{in} + \Delta T, t) \tag{11}$$

$$C_{SR,bui} = \frac{\Delta Q}{COP_{sys}} \tag{12}$$

$$C_{SR,nr} = C_{SR,bui} \cdot \frac{\sum E_{nr,m}}{\sum E_{bui}} \tag{13}$$

6.2.3 Results and discussion

Simulation software TRNSYS is utilized to simulate the “real” hourly heating/cooling loads of the building and to identify the parameters of the proposed simplified model. The detailed process used can refer to the literature [95]. The input variables including the patterns of occupancy, equipment, and light and their proportions for sensible and latent heat as well as fresh air flow rate can all be found in another publication [101]. The identified parameters and coefficients of the building storage model are shown in Table 5. It is worth of noticing that the potential of HVAC systems for providing spinning reserve is an equation of permitted indoor temperature rise (ΔT) and spinning reserve duration (t) rather the time or outdoor temperature. Fig.9 shows the spinning reserve potential capacity ($C_{SR,nr}$) under different allowed temperature rise (i.e., 1K, 2K and 3K) at different time durations (i.e., 10, 20 and 30 minutes).

Table 5 Identified parameters and coefficients of the compact building storage model

Building type	C_{bui} (J/m^2·k)	$R_{bui,o}$ (m^2·k/W)	$R_{bui,i}$ (m^2·k/W)	τ (s)
Medium weighted	248621	0.9236	0.2133	1723.46

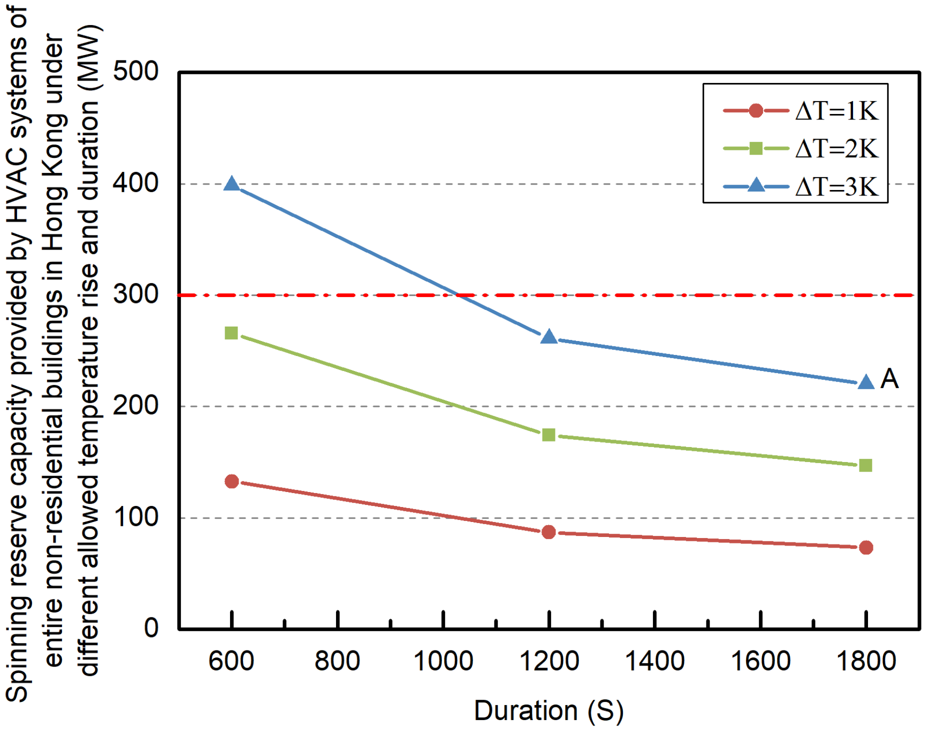

Fig.9. Spinning reserve capacity provided by HVAC systems of entire non-residential buildings in Hong Kong under different allowed temperature rise (ΔT) and duration

It can be observed, the spinning reserve capacity is approximately proportional to the allowed temperature rise, meaning that the more indoor temperature rise occupants can accept, the more cooling power use can be reduced. On the other hand, the spinning reserve capacity declines with the increase of required spinning reserve duration. With the same allowed temperature rise, more reduction of building cooling power use can be achieved when shorter duration of spinning reserve is requested.

In Hong Kong, the capacity of most individual generators installed is about 300MW [102, 103], as shown by the red dash dot line in the figure. The point *A* (in the figure) means that when there is a sudden loss of a generator, up to 220MW (about 73.3% spinning reserve required) can be provided by all HVAC systems in Hong Kong (in office hours), with a sacrifice of thermal comfort (i.e. indoor temperature rise of 3K) when the emergency lasts for 30 minutes. In terms of percentage, the peak demand of Hong Kong in 2017 is 10,696 MW [104], the available capacity can contribute as much as 68.7% to 82.4% of the spinning reserve required typically by the grid (2.5%-3% of the grid power use [42]).

7. Conclusion

This paper presents a comprehensive review on the development of grid-responsive buildings and including: the opportunities, challenges and capabilities of non-residential buildings in providing ancillary services to smart power grid and the methods and technologies concerned. The main conclusions are summarized as follows.

Demand side has many advantages for providing ancillary services compared with the supply side, including larger variability and faster response speed than most generators. It can also contribute to the efficiency of power generation and the operation life of generators. HVAC systems in building sector have two main advantages for providing ancillary services compared with other demand side sources. The first one is their large proportion of electric power use. The other is that HVAC systems can take full use of the internal mass of buildings as a natural thermal energy storage. Furthermore, HVAC systems, especially for those in non-residential buildings, can use existing building automation systems. The use of available storages and existing automation system could reduce the initial investments significantly compared with investing the extra reserve capacities at supply side. The components that equipped with variable-frequency drives (VFDs) are more favorable to provide frequency regulation.

Two challenges commonly encountered when using HVAC systems for providing both frequency regulation and spinning reserve are summarized, including the impacts of the activated components on other associated components and on the built environment control. When providing frequency regulation, other challenges could be also encountered, including the impacts on the energy efficiencies of the components themselves, the response delay and limitations due to the component characteristics and working conditions. When providing spinning reserve, the uneven cooling distribution and problem of rebound effects will be encountered. On the other hand, efforts on developing new control strategies have been made to cope with the challenges raising from providing ancillary services by HVAC systems.

The quantification of ancillary services potentials provided by HVAC systems in buildings is also conducted. During the summer period (from June to October), the potentially available frequency regulation capacities provided by AHU fans of HVAC systems, if one third of non-residential buildings participate, can contribute almost half of the frequency regulation capacity needed in Hong Kong. In office hour, about 220MW spinning reserve capacity can be provided by

HVAC systems of all non-residential buildings in Hong Kong if 3K of indoor temperature rise is allowed and the emergency operation lasts for 30 minutes. This available capacity can contribute as much as 68.7% to 82.4% of capacity typically required by the grid at peak demand.

It is recommended to conduct more experiment studies to quantify “side-effects”, including the effects on building environment control and services quality as well as the power use of associated components when variable-speed fans and pumps as well as the control of constant and variable chillers are engaged for providing frequency regulation.

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