Energy Conversion and Management 102 (2015) 239–246

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A novel air-conditioning system for proactive power demand response to smart grid ☆

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ARTICLE INFO

Article history:
Available online 19 October 2014

Keywords:
Proactive demand response
Smart grid
Chilled water storage
Temperature and humidity independent control
Air-conditioning systems

ABSTRACT

Power demand response is considered as one of the most promising solutions in relieving the power imbalance of an electrical grid that results a series of critical problems to the gird and end-users. In order to effectively make use of the demand response potentials of buildings, this paper presents a novel air-conditioning system with proactive demand control for daily load shifting and real time power balance in the developing smart grid. This system consists of a chilled water storage system (CWS) and a temperature and humidity independent control (THIC) air-conditioning system, which can significantly reduce the storage volume of the chilled water tank and effectively enable a building with more flexibility in changing its electricity usage patterns. The power demand of the proposed air-conditioning system can be flexibly controlled as desired by implementing two types of demand response strategies: demand side bidding (DSB) strategy and demand as frequency controlled reserve (DFR) strategy, in respond to the day-ahead and hour-ahead power change requirements of the grid, respectively. Considerable benefits (e.g., energy and cost savings) can be achieved for both the electricity utilities and building owners under incentive pricing or tariffs. A case study is conducted in a simulation platform to demonstrate the application of the proposed system in an office building.

1. Introduction

One of the biggest challenges encountered by electric grids is the power imbalance between the supply side and demand side, which may cause a series of problems such as low efficiency, surplus energy waste, high pollutant emission, and voltage sags and facilities damages. This imbalance has been further exacerbating with the wide integration of renewable generations (e.g., solar photovoltaic and wind farm) and the rapid increase in comfort cooling or air conditioning (A/C) usage in many countries [1]. Smart grid that can help reduce the grid imbalance by jointly controlling both the power production on the supply side and the power consumption on the demand side is therefore considered as a promising solution by many researchers [2–4]. The control of power demand of end-users in response to grid signals (e.g. dynamic price and reliability information) is known as demand response (DR) and has become an essential part in the smart grid vision [5,6]. Based on the type of signal used to activate the DR program, DR programs can be categorized as either emergency (or reliability based) DR programs or economic (price based) DR programs or demand side ancillary service programs [7].

Buildings, as a primary end-users consuming about 30% of the total electricity in US [8] and over 90% of the total electricity in Hong Kong [9], can play an important role in power demand response. Many demand response measures have been employed in buildings to reduce or shift power demand during peak demand periods. In residential buildings, demand response measures are typically invoked for active shutting down the large consumers (e.g., A/C, washers and heaters) during peak periods, thereby reducing electricity consumption as well as minimizing simultaneous power demands by participating households [10]. In commercial buildings, building thermal mass (i.e., passive storage) and thermal storage systems (i.e., active storage) are usually used to shift the heating/cooling load and consequently the power demand from the peak periods to the off-peak periods. For instance, Braun [11] evaluated the performance of different building thermal mass control strategies, which control the building cooling demand by adjusting the set-points of indoor-air temperature. Sun et al. [12] proposed a demand limiting strategy by utilizing building thermal mass for pre-cooling building in early morning hours. The main drawback

☆ This article is based on a four-page proceedings paper in Energy Procedia Volume 61 (2015). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal.

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http://dx.doi.org/10.1016/j.enconman.2014.09.072
0196-8904/

of using thermal mass is that the storage capacity and efficiency are low and the controllability of cold energy discharge is poor [13]. The amount and duration of the thermal mass storage vary widely, depending on various factors including building structure, thermal time constants, and internal and external heat gains [14]. In addition, using thermal mass for power demand control has a certain degree of impact on the thermal comfort of occupants since the indoor temperature is affected more or less.

By contrast, using the active thermal storage has larger capacity and better controllability in peak load reduction while has less negative impact on building occupants. It reduces building peak demand through the production and storage of cold energy during off-peak periods and the usage of the stored energy for cooling during peak periods. The cold energy is usually stored in the form of ice, chilled water, phase change materials (PCMs) or eutectic solution [15,16]. Among them, chilled water storage (CWS) and ice storage are the most prevalent techniques that are commonly used worldwide. Compared with the ice storage system, the chilled water storage system has many attractive advantages such as simple system configuration, easy control strategy and low initial and operating cost [17]. However, the volumetric thermal storage density of the chilled water storage system is much less than that of the ice storage system. For storing the same amount of cold energy, the required volume for a chilled water storage is about 5–8 times of that of an ice storage system [18]. The requirement of large storage tank and consequently high storage construction cost are the main obstacle to apply the chilled water storage system in buildings. Fortunately, some measures such as reducing the amount of cold energy storage and increasing the storage density through enlarging the water temperature difference can be used to reduce the required storage volume of a chilled water storage system.

The temperature difference of a CWS system is mainly determined by the supply temperature of the chiller and the return temperature from A/C terminals. In conventional air-conditioning systems by which air is cooled and dehumidified (i.e., moisture is removed by condensation) simultaneously, the supply and return temperatures of chilled water are usually fixed to be 7 °C and 12 °C respectively. If a CWS is adopted in such an air-conditioning system, the temperature difference of the CWS system is no more than 5 °C (considering the temperature differential loss due to heat exchangers). However, in temperature and humidity independent control (THIC) air-conditioning systems (also called as "independent control of temperature and humidity system"), the indoor air temperature and humidity can be regulated independently using a separate temperature control subsystem and a humidity control subsystem respectively [19]. The return water temperature from the cooling coils of the temperature control subsystem can be increased significantly (e.g., from 12 °C to 21 °C) and the storage density of CWS can be increased consequently. In addition, the sensible cooling load can be separated from the latent load (moisture load). If only the sensible cooling load (about 50–60% of the total cooling load) is stored, the volume of the required storage tank can be further reduced when comparing with the conventional chilled water storage systems that need to store the entire total cooling load.

In order to effectively make use of the demand response potentials of the chilled water system and reduce the required storage volume, a novel air-conditioning system, which combines a chilled water storage system (CWS) with a temperature and humidity independent control (THIC) air-conditioning system, is proposed in this paper. Through scheduling and optimizing the charge and discharge of the chilled water system, the building can effectively control the power demand of the air-conditioning system in respond to the day-ahead and hour-ahead alteration requirements of the grid.

2. System configuration and operation modes

2.1. System configuration

Fig. 1 illustrates the schematic of the proposed air-conditioning system. The cold source of the system consists of chillers and a chilled water storage tank. Ideally, the chilled water is stored inside the tank in stratified layers for later use in meeting cooling needs. During the discharge mode, chilled water is supplied from the bottom of the tank and is returned to the top of the tank at low flow rates to minimize mixing of the layers [20]. The cooling capacity of the system mainly depends on the temperature differential across the stratified storage tank (i.e., the temperature difference of the CWS system), as shown in Eq. (1).

$$V_{tank} \propto \frac{Q_S}{\Delta T} \tag{1}$$

where V_{tank} is the required storage volume of the water tank. Q_s is the storage capacity of the tank. ΔT is the temperature difference of the CWS system, which equals the difference between the return water temperature (i.e., T_R) to the tank and the supply water temperature (i.e., T_S) from the tank.

The terminal system consists of two subsystems, i.e., the humidity control subsystem and the temperature control subsystem which are used to control the humidity and temperature of indoor air respectively. The humidity control subsystem is a dedicated fresh air system (e.g., AHUs (air handle units)) and the temperature control subsystem is a room terminal system (e.g., dry FCUs (fan coil units) or radiant ceiling). In the humidity control subsystem, the outdoor fresh air is dehumidified in the AHU coils using the low-temperature chilled water from chiller (or from tank for a short period of time). The dehumidified air (i.e., dry air) is then supplied to the room for handling the entire indoor latent (or moisture) load and part of sensible load as the supplied air temperature (e.g., 13 °C) is lower than the indoor air temperature. The rest sensible load is removed using the FCUs or radiant ceiling room terminals in the temperature control subsystem. Without the need for dehumidifying in the room terminals, the required supply/return chilled water temperature can be increased significantly, e.g., from the conventional 7 °C/12 °C to 18 °C/21 °C.

Typically, the high temperature chilled water should be provided by a high-temperature chiller (with supply/return temperature of 18 °C/21 °C) rather than by a conventional chiller (with supply/return temperature of 18 °C/21 °C) since the COP of former is much higher (e.g., 30%) than the latter one. However, in the proposed system, the chilled water is provided from the storage tank, in which the chilled water is still produced by conventional chiller with a relative lower COP. In this way, the energy performance of the system is not as good as the typical case. The benefit is that the temperature difference of the CWS system is increased significantly (e.g., from 5 °C to 14 °C), which helps reduce the required storage volume correspondingly, as indicated by Eq. (1).

2.2. System operation modes

Four difference modes can be operated in this proposed system: (1) *cold charging mode*, (2) *cold discharging mode*, (3) *cold overdrawing mode* and, (4) *cold repaying mode*. The specific operating status of key equipment and valves under these four modes are shown in Table 1. During the off-peak periods (e.g., nighttime), the system operates in *cold charging mode*: all chillers are switch on to produce cold energy that is stored in the water tank with a temperature about 6 °C. During the normal office hours, the system operates in *cold discharging mode*: the stored cold energy is extracted from the tank through heat exchangers (i.e., EX2 in the figure) to handle the cooling load of FCUs in the temperature control subsystem.

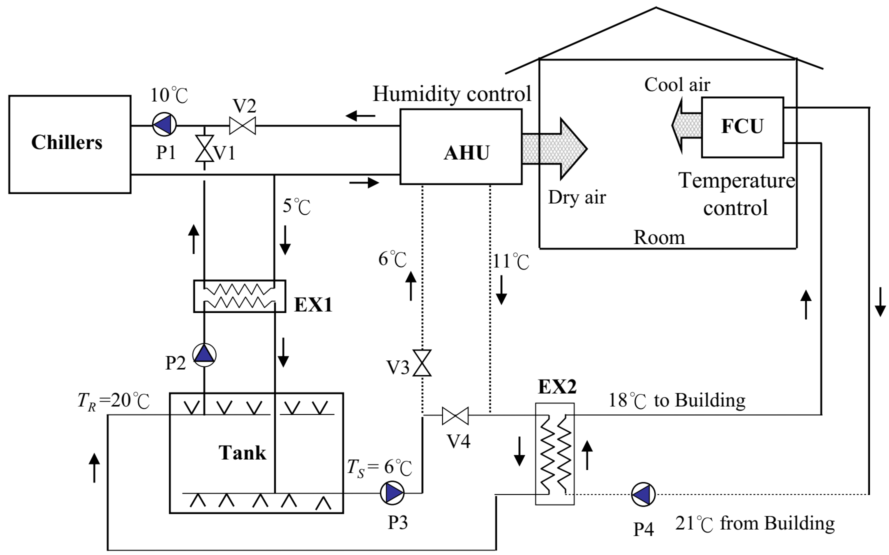

Fig. 1. Schematic of the temperature and humidity independent control (THIC) system using chilled water storage (CWS).

Table 1
Operating status of equipment and valves under four operation modes.

Operating mode	Chillers	Terminals		Pumps				Exchangers		Valves			
		AHU	FCU	P1	P2	P3	P4	EX1	EX2	V1	V2	V3	V4
Cold charging	✓	×	×	✓	✓	×	×	✓	×	✓	×	×	×
Cold discharging	✓	✓	✓	✓	×	✓	✓	×	✓	×	✓	×	✓
Cold overdrawing	×	✓	✓	×	×	✓	✓	×	✓	×	×	✓	✓
Cold repaying	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓

Remarks: ✓ indicates that the operating status of chillers, AHUs, FCUs, pumps and heat exchanger are ON, or the status of valves are OPEN; × indicates that the operating status of chillers, AHUs, FCUs, pumps and heat exchangers are OFF, or the status of valves are CLOSE.

Meanwhile, only parts of chillers are switched on to supply the chilled water to handle the cooling load of AHUs in the humidity control subsystem. By doing this, the power demand during the office hours period (including the peak period) can be significantly since only about half of the total cooling load need to be handled during this period. In addition, the chiller capacity can also be reduced when comparing with a system that does not use cold storage.

In case that the building power demand needs to be immediately reduced in respond to the real time requirement from the smart grid (i.e., for emergency DR events), the system can operate in the *cold overdrawing mode*: all running chillers can be shut down immediately and the cold energy for handling the cooling load of AHUs in the humidity control subsystem can also be provided by the tank (through the branch indicated by dotted line in Fig. 1). The overdrawn cold energy needs to be repaid to the tank after the DR events. Otherwise, the left cold energy in the storage tank might not be enough for handling the cooling load of the temperature control subsystem in the followed periods. As a result, a cold overdrawing mode is always followed by a *cold repaying mode* where all chillers are switched on to produce the cold energy as much as possible. A part of the cold energy is used to handle the cooling load of AHU and the rest is stored in the storage tank for repaying the overdrawn cold energy.

3. Implementation of proactive demand response strategies

Existing power demand response strategies are usually realized in a passive pattern: temperately sacrificing the indoor environment (e.g., dimming lights or increasing the set-point temperatures in cooling season) for load shedding during peak demand periods. Such passive actions may result in an uncomfortable or unacceptable indoor environment and then may impair occupants' performance since the temperature and illuminance are deviated from the intended values. By contrast, producing and storing more cold energy in advance and using the stored energy for cooling supply during the peak periods is a more active way for demand response. Using the proposed air-conditioning system, the chilled water storage system enables the building to provide a proactive way for power demand response. The term proactive is used to address that the power demand reduction is realized by shifting the load from peak periods to off-peak periods actively in advance rather than by tolerating the indoor environment sacrificing passively. Two proactive demand response strategies, which are demand side bidding (DSB) strategy and demand as frequency controlled reserve (DFR) strategy in respond to the day-ahead and hour-ahead demand alteration requirements from the grid respectively, are proposed in this study. The DSB strategy can be realized by operating the system in the cold charging mode and cold discharging mode. The DFR strategy can be realized by the system operating in cold overdrawing mode and cold repaying mode.

3.1. Day-ahead demand side bidding (DSB)

Demand side bidding (DSB) is a competitive mechanism which enables the demand side of the grid to participate in electricity bargaining. A day-ahead demand-side optimization provides the supply-side with an estimation of the amount of energy to be delivered to the demand-side during the upcoming day [21]. DSB can improve the efficiency of the electricity supply chain by increasing competition in the wholesale energy market and by acting as an alternative to conventional generation. For example, DSB can be used to balance electricity supply and demand and also maintain the quality and security of supply. The success of implementing demand response (e.g., DSB) is mainly dependent upon the capabilities of end-users in altering their loads with a favorable manner for both the power suppliers and end-users [22].

For implementing the DSB strategy, buildings have to respond to the day-ahead electricity prices adequately in order to reap the greatest benefits in operation cost. The day-ahead electricity price are determined by the submitted power supply offers and power demand bids according to pre-set electricity market rules and bidding mechanisms. Generally, the prices in off-peak periods are much lower than that in peak periods, as shown in Fig. 2. As a result, buildings are willing to shifting their electricity usage to the off-peak period. However, the alteration capabilities highly depend on the characteristics and constraints of their building service systems.

In the proposed air-conditioning system, a considerable amount of cold energy can be produced during the off-peak periods with a relative low price and stored in the chilled water tank (i.e., *cold charging mode*). During the office hours, the stored cold energy can be discharged for handling the sensible cooling load and only the latent and fresh air loads need to be provided by chillers (i.e., *cold discharging mode*). As a result, the original cooling load profile (without storage system) can be adjusted to the altered one, as shown in Fig. 3. This kind of arrangement can result a great power demand reduction during the peak periods because chillers usually dominate the power demand of a building and the chiller power is nearly proportionate to the provided cooling load.

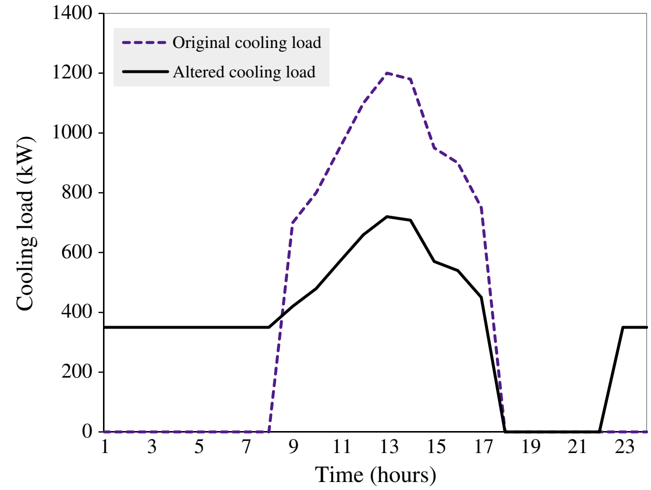

Fig. 3. Illustration of building cooling load alteration when using DSB.

3.2. Demand as frequency controlled reserve (DFR)

The other proactive demand response strategy, i.e., demand as frequency controlled reserve (DFR) strategy, can be implemented in the proposed air-conditioning system in response to the hour-ahead demand alteration requirements from the grid based on the basis of DSB strategy. As mentioned above, a day-ahead DSB strategy can help a grid to be more secure and energy efficient. However, power imbalance is still likely to occur in sub-hour (e.g., in half-hour) periods due to either inaccuracies in the load prediction or unscheduled changes in the supply/demand (e.g., emergency events happened). Such power imbalance causes either the power surplus or power shortage, which results in energy waste or complaints from end-users. A more critical issue is that the power imbalance may cause the frequency of the grid to be unstable which is very harmful to the healthy operation of the grid. In order to maintain a stable frequency in the grid, extra capacities (e.g., spinning reserve of generators) from the generation supply side are primarily used to balance the power supply and demand in real time. The result is extreme electricity price volatility on days when the load is high [23,24]. As an alternative option, demand as frequency controlled reserve (DFR), also called dynamic demand, becomes a more cost-effective solution to help maintaining grid frequency by rapidly adjusting end-users' load at demand side when the power imbalance happens in real time [25].

When using the proposed air-conditioning system, the DFR strategy (e.g., emergency demand response program) can be realized by switching off some or all operating chillers immediately in respond to the real time power reduction requirements while having no impact on the indoor thermal comfort. When the power shortage on the grid is predicted to be happened in the next short period in advance (e.g., from 12:45 to 13:15 in Fig. 4), the signals for requesting power reduction (e.g., reduction amount and associated duration) will be sent to DR participants. Once the signal is received by the building, chillers can then be switched off (i.e., *cold*

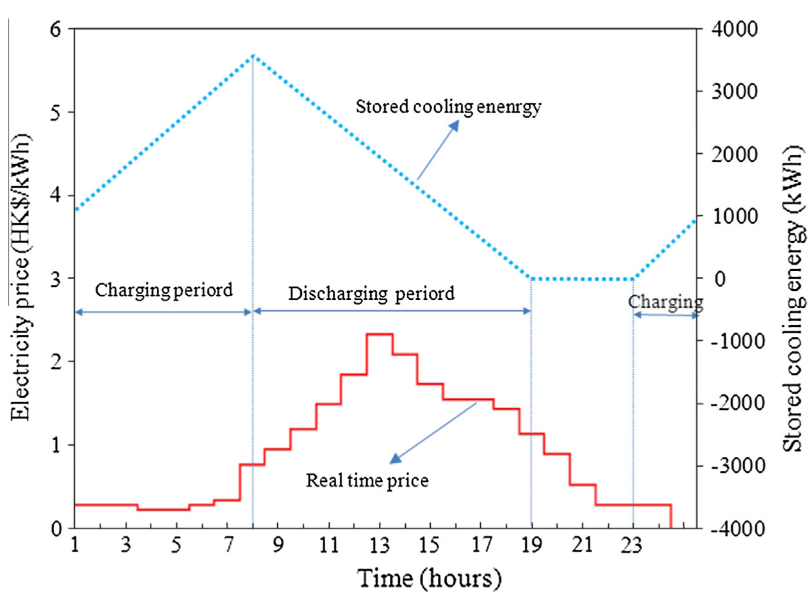

Fig. 2. Conceptual day-ahead pricing and storage arrangement when using DSB.

overdrawing mode) for a period of time (e.g., hours). During this period, in addition to supply cold energy to the temperature control subsystem for handing the load in FCUs, the chilled water storage tank also needs to provide cold energy (i.e., overdraw the stored cold energy) to the humidity control subsystem for handing the load in AHUs. Conversely, when the power is predicted to be surplus on the grid in the next short period of time (e.g., from 15:00 to 16:00 in Fig. 4), the overdrawn cold energy in the storage tank can be compensated by producing more chilled water by running more chillers (i.e., *cold repaying mode*).

In order to encourage end-users to participate the DFR strategy, attractive tariffs (payments) from the suppliers should be paid to the participators based on the change of the load level (including reduction or increase) achieved according to the demand response contracts signed in advance. In this point of view, extra benefits in operation energy cost can be achieved by the proposed air-conditioning system during both the cold overdrawing and repaying periods.

4. Case study

A case study on the utilization of the proposed air-conditioning system for demand response to the smart grid is conducted in a virtual building through detailed simulations in EnergyPlus that is recognized as one of the best dynamic energy calculation tool [26]. The power demand response performances of using DSB and DFR strategies are evaluated.

4.1. Building information and electricity price

A 40-storey office building in Hong Kong is modeled for the computer simulation in this study. Most electricity (over 90%) is used by buildings for lighting and air-conditioning in subtropical Hong Kong, where the summer is long, hot and humid. A long cooling season (lasting from late March to early November) causes the air-conditioning to contribute 50–60% of the total electricity use. There is no actual data of day-ahead price or real time price in Hong Kong and the current electricity price policy is time-of-use (TOU) plus peak demand charge [27]. In this study, a synthetic dynamic electricity price curve of Hong Kong future' smart grid market is estimated to illustrate the evolvement of price throughout the year, as shown in Fig. 5. It can be observed that the electricity price varies significantly from hour to hour, day to day, and season to season. By shifting the power demand from the high-price periods to the low-price periods therefore can achieve a great cost saving. This electricity curve is based on the basis of the day-ahead price data in New York in 2013 and corrected according to the annual average electricity price in New York and Hong Kong, as shown in Eq. (2).

$$P(\tau)_{HK} = \frac{P_{Average,HK}}{P_{Average,NY}} P(\tau)_{NY} \qquad (2)$$

where $P(\tau)_{HK}$ is the estimated electricity price of Hong Kong in τ hour. $P(\tau)_{NY}$ is the actual electricity price of New York in τ hour in 2013. $P_{Average,HK}$ and $P_{Average,NY}$ are the annual average electricity price of commercial sector in 2013, which are about HK $1.1 per kW h in Hong Kong and USD $0.15 per kW h in New York respectively [27,28].

The configuration of this building is referenced from a generic office building that can be used as a reprehensive office building in Hong Kong [29]. The building is 35 × 35 m with a 14 × 14 m non-air-conditioned central core, which indicates that the total gross floor area and air-conditioned area are 49,000 m^2 and 41,160 m^2, respectively. The window-to-wall ratio (WWR) is 0.44 with single reflective glass which has a solar heat gain coefficient (SHGC) of 0.4. The *U*-values for wall and windows are 2.5 and 5.6 W/m^2 K, respectively. The set point of indoor temperature and relative humidity are 25 °C and 50%, respectively. Electric lighting is recessed fluorescent with a lighting load of 10.8 W/m^2. Office equipment load is 8.1 W/m^2 and the occupancy density is 18 m^2/person. The building and its lighting system operated on an 14 h day (07:00–21:00) and 5 day week basis. More details of this reprehensive office building can be found in Ref. [29].

Two air-conditioning systems are compared in this case study. The first one is a conventional system without cold storage, e.g. a typical air–water system consisting of dedicated fresh air handling units (AHUs) and fan coil units (FCUs). The second one is the proposed system (see Fig. 1). A stratified CWS that is acknowledged as the simplest method of chilled water storage is adopted in the proposed system. Stratified chilled water storage tanks rely on the tendency of water to form horizontal layers or temperature zones based on its density. Stratified storage tanks achieve the necessary separation between the cold and warm water by creating and maintaining a thermocline layer between the warm upper zone and the cool lower zone [20]. More detailed analysis of the charging and discharging performance (e.g., the dynamic temperature profiles) of thermally stratified chilled water storage systems can be found in Ref. [30]. Except for the additional equipment of the proposed system (such as water tank, extra pumps and heat exchangers), all other equipment of two systems including chillers,

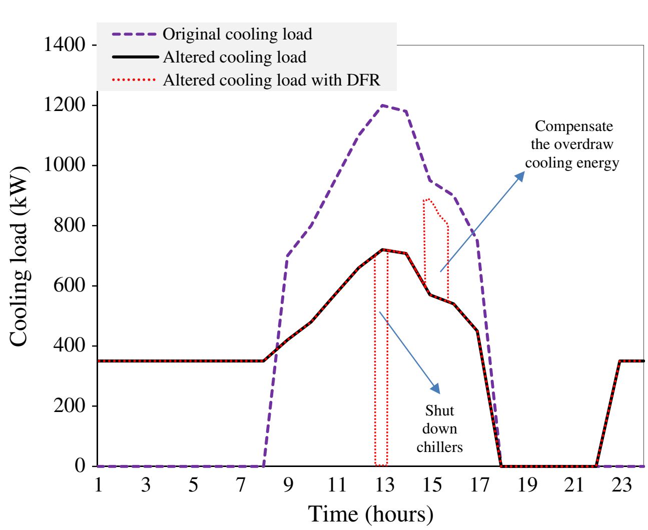

Fig. 4. Building cooling load alternation when combining DSB and DFR.

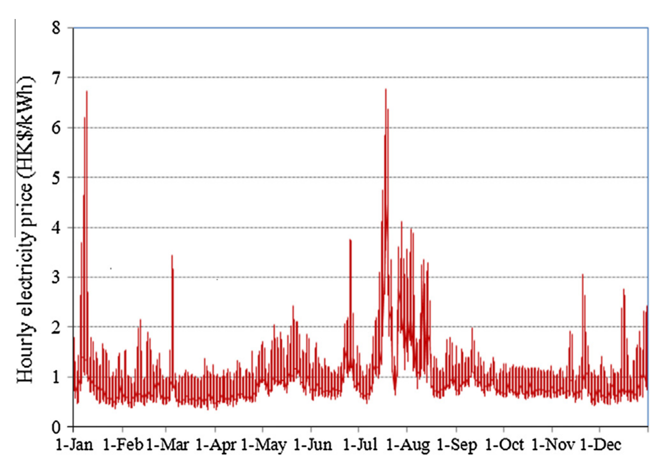

Fig. 5. Synthetic dynamic electricity price curve in Hong Kong future's smart grid.

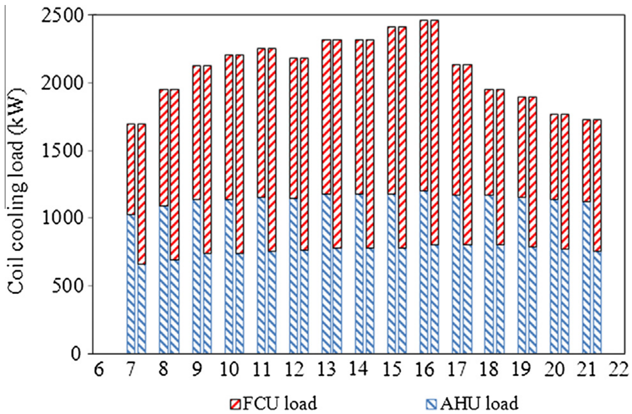

Fig. 6. Coil loads of AHUs and FCUs when using two different systems.

chilled water and condenser water pumps as well as AHU and FCU fans are the same. The conventional system, which does not use cold storage and therefore has no demand alteration ability, is used as the baseline for benchmarking the demand response performance of the proposed system.

4.2. Power demand response performance evaluation

The energy performances of above two air-conditioning systems on the design day (i.e., peak load day) are simulated using EnergyPlus. The building cooling load during occupancy period (i.e., 7:00–21:00) is shown in Fig. 6. Both systems use FCUs and AHUs to handle space cooling load and outdoor fresh air ventilation load. The sums of FCU load and AHU load of these two systems are the same while the load distributions between FCUs and AHUs are different. Using the conventional system (the right column), all space cooling loads are handled by FCUs and the fresh air load is handled by AHUs when the outdoor fresh air is conditioned to the same enthalpy state as indoor air. However, when using the proposed system (the left column), besides the fresh air load, AHUs can also handle a part of space cooling load, including all latent load (e.g., moisture load of occupants) and a small part of sensible load since the dehumidified supply air with much lower humidity and temperature (e.g., 13 °C) than that of indoor air. As a result, the AHUs loads are larger than that of the conventional system.

Using the conventional air-conditioning system, the hourly refrigeration load (determining the chiller power demand) of chiller equals to the hourly building cooling load. However, using the proposed system, the FCU load is shifted to night and only the AHU load needs to be handled in daytimes. As a result, chiller's

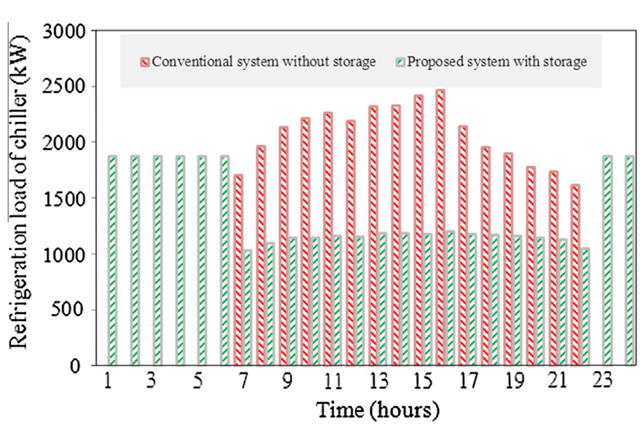

Fig. 7. Refrigeration load of chiller when using two different systems.

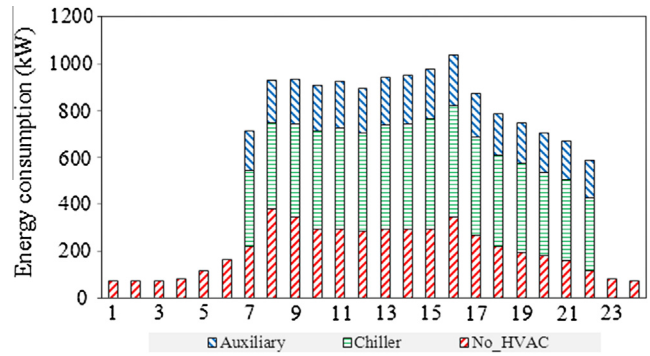

Fig. 8. Power demand of the building when using the conventional system.

refrigeration load profiles of two air-conditioning systems are significantly different, as shown in Fig. 7.

4.2.1. The performance of demand side bidding (DSB)

The performance when only using the day-ahead demand side bidding (DSB) strategy is firstly evaluated. Due to the chiller load shifting, the power demand of chiller and auxiliary components are altered consequently. The total building power demands of two systems are shown in Figs. 8 and 9. It can be observed that the original power demand (i.e., using the conventional air-conditioning system) is significantly improved by using the proposed systems. The power load factor (i.e., the average power divided by the peak power over a period of time) is increased from 57.5% to 86.6%, which proves that the proposed system has very good performance on the demand response to the electricity grid.

Great cost saving can be achieved in the building by shifting the power consumption from the peak load period to the off-peak period. Due to the extra pump consumption and the energy lose during the cold storage process, the building may consume a little bit more energy (e.g., 2.6% in this case study) using the proposed system than that of using the conventional system. However, the total energy cost of the building on the design day is reduced by 29.7% using the hourly electricity price given in Fig. 2. In addition, the chiller capacity of the proposed system is also about 24% smaller than that of the conventional system, which can greatly reduce the initial cost of the air-conditioning system. The storage volume of the chilled water tank is about 920 m^3. In fact, these benefits can be achieved by the traditional chilled water storage system that does not use the THIC technology and therefore has a relative low storage temperature difference of 5 °C. But the required storage volume of the tank should be 2580 m^3, which is 2.8 times of the present volume.

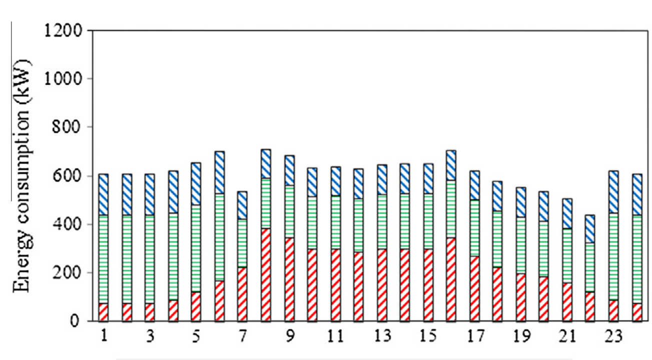

Fig. 9. Power demand of the building when using the proposed system (with DSB strategy).

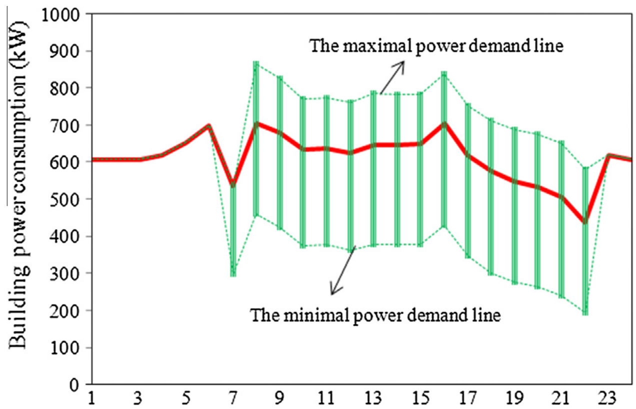

Fig. 10. The potential of building power demand alteration using DFR strategy.

4.2.2. The performance of demand as frequency controlled reserve (DFR)

Based on the day-ahead DSB strategy, the power demand of the building during the peak load period can be further altered (reduce or increase) through the DFR strategy by switching off and/or on chillers in response to the real time power change requirements from the grid. The greatest power alteration potentials of the building including the maximal power demand and the minimal power demand are shown in Fig. 10. The red[1] solid line represents the basic power demand of the building after using DSB. The maximal power demand occurs by operating all chillers with the maximal capacity when the grid has surplus power supply. The surplus cold energy is temporarily stored in the tank. The minimal power demand contributes by no-HVAC loads (e.g., lighting) and auxiliary loads (pumps and fans) when all chillers are switched off in response to the power shortage of the gird. In this case, all cooling loads (FCU loads and AHU loads) are undertaken by the cold storage tank. Taking the average data during the operating period for example, the average basic power demand of the building is 609 kW h while the average values of maximal and minimal power demand are 749 kW h and 343 kW h, respectively. This indicates that the building has the potential to increase 23% or reduce 43% of its power demand in response to the change requirements of the grid.

The cost saving of the building using DFR strategy is large but it is also difficult to quantify so far since it strongly depends on the pre-contracted payment rates (which may be 10 times or even larger than the peak price in general), and the durations and frequency of the DR Events.

5. Discussion of application issues

The aim of this paper is to develop a new air-conditioning system which facilitates the building as an excellent resource for power demand response in future's smart grid while has no impact on building occupants' thermal comfort and reduces the required storage volume. This aim is achieved by combining the chilled water storage and the temperature and humidity independent control. The chilled water storage system is a well acknowledged technique for building demand side management even before the term smart grid became vastly used. The temperature and humidity independent control is a new concept for air-conditioning, which can overcome many drawbacks of conventional air-conditioning system such as energy waste by reheating, low energy efficiency of chiller caused by producing low temperature chilled water [31]. There is no real application of the proposed system in practice so far. Some possible problems and key issues of this system in future's application are discussed as below.

The CWS in this paper is a typical stratified chilled water storage system. It uses conventional water chillers and operates under the same general conditions as for conventional chilled water storage. The only difference is that the temperature differential across the stratified storage tank is much larger than that of conventional CWS, which is beneficial for improving the storage efficiency because the larger temperature differential of a CWS, the better separation performance achieves.

In order to improve the cost-effectiveness, the storage tank for chilled water may also serve as reservoirs for fire protection water, thus providing the owner with a savings in capital costs and possibly in insurance premiums. There are real examples that existing fire protection reservoirs are successfully converted into stratified thermal storage reservoirs [20]. In addition, these two heat exchangers (i.e., EX1 and EX2) and associated pumps (i.e., P2 and P4) in Fig. 1 can be deleted in theory, which can further reduce the initial cost and avoid the additional loss of temperature differences during heat exchanging process. However, the deletion of them may cause some problems in system operation such as quality deterioration of chilled water and fouling in chiller evaporators and cooling coils. In a temperature and humidity independent control system, the required absolute moisture content of the supply air in the humidity control subsystem is very low (e.g., 8 g/kg dry air) because all indoor and fresh air moisture loads of the building are needed to be removed by this subsystem. Liquid desiccant system is the most used method to handle the supply air with so low absolute moisture content [31]. In this study, the humidity control is still uses conventional condensation dehumidifying method through AHUs, which is much cheaper than using liquid desiccant systems. The low absolute moisture content can also be achieved by using the AHUs with more coil rows (e.g., coils with 6 or 8 rows) or reducing the supply temperature of chilled water properly.

6. Conclusion

A novel air-conditioning system, which combines a chilled water storage system (CWS) and a temperature and humidity independent control (THIC) system, is developed for proactive demand response to the smart grid. Four different operation modes with different cooling and power demands can be realized in the developed system. By proper switching among these operation modes, two demand response strategies, i.e., the demand side bidding (DSB) strategy and demand as frequency controlled reserve (DFR) strategy can be implemented in a building in response to the day-ahead and hour-ahead power balance requirements of the grid, respectively.

The demand response performances of these two strategies are evaluated in an office building in Hong Kong through a simulation case study in EnergyPlus. Results show that considerable benefits can be achieved for both electricity utilities and end-users. Compared with conventional air-conditioning system, the power load factor of the building increased from 57.5% to 86.6% by using the DSB strategy. Furthermore, the building can flexibly change (e.g., increase by 23% or reduce by 43%) the power demand using the DFR strategy in response to the needs of the grid. For the end-users of the building, the chiller capacity is reduced by 24% and the total energy cost can be reduced by 29.7% that still does not include the extra payments from using DFR. Comparing with the traditional chilled water storage without combining the THIC (temperature and humidity independent control), the required volume of the storage tank can be reduced by 64.3%.

[1] For interpretation of color in Fig. 10, the reader is referred to the web version of this article.

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