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 ☆

Chengchu Yan, Xue Xue, Shengwei Wang *, Borui Cui

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong

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.

* Corresponding author. Tel.: +852 27665858; fax: +852 27746146.
E-mail address: beswwang@polyu.edu.hk (S. Wang).

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.