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A direct load control strategy of centralized air-conditioning systems for building fast demand response to urgent requests of smart grids

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ABSTRACT

When receiving an urgent request from a smart grid, shutting down part of operating chillers directly in the air-conditioning system in a building can achieve immediate power reduction. However, no study has addressed how to determine the number of chillers/pumps to be shut down and how to regulate the load of retained equipment systematically during DR events. This paper presents a new approach to address these issues based on three schemes. A power demand optimization scheme predicts the building cooling demand and the power limiting threshold in response to a received DR request. A system sequence control resetting scheme determines the number of operating chillers/pumps to be retained. An online control/regulation scheme ensures the system power following the expected profile by regulating the total chilled water flow delivered to the building and therefore the chiller load. It also employs a cooling distributor to distribute chilled water to individual zones concerning different sensitivities/sacrifices to temperature increases. Case studies are conducted on a simulated dynamic building air-conditioning system. Results show that, during DR events, the proposed strategy can achieve the expected power reduction (i.e., about 23%) and also maintain acceptable zone temperature even though uncertainties exist in the prediction process.

1. Introduction

The power balance between the supply side and the demand side of a power grid is a critical issue in grid operation. However, the rapid growth of power demand and the integration of large amounts of renewable generation, which heavily depends on the weather conditions, impose a huge stress on the balance of the power grid [1–3]. Any power imbalance will cause severe consequences in the reliability and quality of power supply (e.g., voltage fluctuations and even power outrages) [4]. Facing the challenges from the power imbalance, the smart grid is considered as a very promoting solution to incorporate advanced technologies to offer better flexibility, reliability and security in grid operation. A smart grid improves the communication ability between power producers and consumers to make decisions about how and when to produce and consume electrical power [5]. The control of power demand at the consumer side in response to grid requests (e.g., dynamic price and reliability information) is known as demand response (DR) [6]. DR programmes can benefit power grids in reducing peak loads and hence avoid huge investments in upgrading the grids [7]. They can also provide considerable economic benefits for building owners [8,9].

Among different kinds of consumers at the power demand side, buildings are one of the major energy consumers today and their share is increasing due to the urbanization. Considering the elastic nature of building energy use, the interaction between buildings and power grids could be very promising. Moreover, with the help of advanced technologies such as building automation systems and smart meters, demand response control strategies in buildings could be implemented to realize this bidirectional operation mode between buildings and power grids [10,11]. Heating, ventilation, and air-conditioning (HVAC) systems, accounting for > 50% of energy used in buildings in the USA [12], are excellent demand response resources to reduce or shift the electricity demand during peak periods [13].

Load shifting, which is the process of shifting on-peak loads to off-peak hours so as to take advantage of electricity rate difference in different periods, is more commonly-used for demand side management in commercial buildings. Many studies have been conducted on load shifting [14–17]. Xu and Haves [18] conducted a preliminary case study to demonstrate the potential of utilizing building thermal mass for peak demand reduction in an office building in California. Two precooling and zone temperature reset strategies were tested. The results pointed out that the limiting control strategy could reduce the

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chiller power significantly. Sun et al. [19] conducted case studies concerning the peak demand reduction to minimize energy cost and peak demand charge using an indoor air temperature set-point reset strategy that achieved significant power reduction on HVAC systems during peak hours. However, due to inevitable energy losses in the power charging and discharging processes, the peak load reduction is realized at the expense of increasing energy consumption. In addition, resetting the indoor air temperature cannot achieve significantly immediate power reduction within a very short time interval (i.e., minutes) resulting from the inherent and significant delay of charging and discharging control processes [20].

Facing urgent requests and incentives from smart grids, direct load control (DLC) is considered as an effective way to achieve immediate power reduction within a very short time. Direct load control means that electricity utilities have the permission to control (e.g., switch off) the specific devices/systems of end-users and give a certain incentive to them based on their previous agreements (e.g., contracts) [21,22]. Many studies on DLC have been conducted, particularly for residential buildings. DLC is considered as an effective means to achieve power reduction and provide frequency regulation services [23,24]. The frequency regulation services are used to deal with the grid imbalance from the viewpoint of power demand side, which also have the requirement on response time. The main objective of frequency regulation is to modify the power use on the demand side to match the power supply. The modulation required to provide frequency regulation cannot be achieved with residential cooling equipment that does not incorporate variable-speed drives for the refrigerant compressor motor. Moreover, DLC for frequency regulation makes economic sense for very small cooling systems.

In fact, the power demand of chillers accounts for a large part of power use in commercial buildings using centralized air-conditioning systems. When power grids need an immediate and significant power reduction on the demand side, shutting down some of operating chillers directly in a commercial building turns out to be effective, which is a typical DLC programme and has been applied in real projects in some areas. For example, in Hong Kong, the utility company, CLP, has recently launched a demand response programme, namely "Automated DR programme", which is actually a direct load control programme. With agreements in advance and devices installed at the customer side, part of operating chillers could be reduced by the utility company automatically and remotely when there is an urgent need in power reduction.

Although shutting down some of operating chillers in commercial buildings can achieve immediate power reduction, the operating states of air-conditioning systems are obviously changed. The authors of this paper pointed out that the unbalanced chilled water distribution in an air-conditioning system would occur after simply shutting down some of operating chillers [25]. A novel supply-based feedback control strategy based on adaptive utility function was developed and effectively solved this problem. However, no previous study was carried out on how to determine the number of chillers to be shut down during DR events from the viewpoint of whole air-conditioning systems. This is because shutting down part of operating chillers would significantly influence the power consumption of equipment other than chillers in an air-conditioning system. In addition, how to regulate the loads of retained equipment in a system to realize expected power limiting threshold is also needed to be discussed.

In this paper, a fast demand response control strategy concerning a typical air-conditioning system (i.e., constant water flow in the primary chilled-water loop and variable water flow in the secondary loop) is developed for proper system control responding to urgent requests from smart grids. The main innovations and original contributions of this research include: (1) a systematic approach is proposed to make such fast demand response method (i.e., shutting down part of operating chillers) effective for urgent requests of smart grids; (2) an power demand optimization scheme is developed to determine the power limiting threshold considering the indoor thermal environment; (3) a system sequence control resetting scheme is proposed to determine the numbers of retained devices in an air-conditioning system during a DR event; (4) an online control/regulation scheme is developed to maintain the system power demand at an expected power profile; (5) a modified cooling distributor is introduced concerning the uncertainty of prediction process. Case studies are conducted to test and validate the effectiveness and performance of this proposed control strategy.

2. Direct load control strategy

2.1. Overall structure and approach

Generally, the power demand of a commercial building is contributed by building services systems, including heating, ventilation and air-conditioning (HVAC) systems, lighting, electrical equipment, lifts and elevators, etc. The total power demand (i.e., electricity load) of a commercial building can be divided into two parts [26]: sheddable power demand and controllable power demand. Electricity loads of lighting, electrical equipment, transportation and other appliances are the sheddable power demands, which can be conveniently obtained according to their operation schedules. In contrast, the electricity loads of HVAC systems are the controllable power demands, which are possible to be altered by power demand controls. In this study, the power reduction of an air-conditioning system in a commercial building is concerned to meet the urgent requests of smart grids.

With a sudden pricing change or an urgent incentive given by a utility company during a DR event, the fast demand response control strategy is activated to realize immediate power reduction. In general, this control strategy implemented in real projects mainly consists of two steps: overall decision-making and control implementation. At the overall decision-making step, the numbers of devices to be shut down and the power limiting threshold are determined. At the control implementation step, the power demand of the air-conditioning system is adjusted to achieve the pre-determined power limiting target during a DR event after shutting down part of operating devices as determined.

The overall structure of the fast demand response control strategy is shown in Fig. 1. It mainly includes the power demand optimization, the

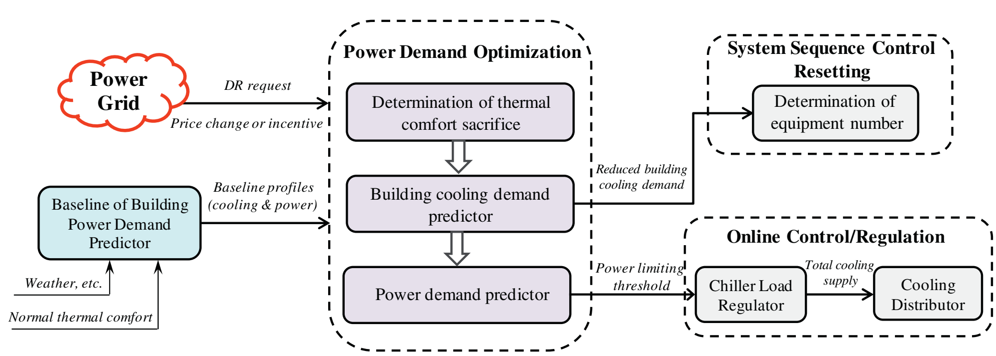

Fig. 1. Basic approach of fast demand response control strategy during DR events.