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Effectiveness and life-cycle cost-benefit analysis of active cold storages for building demand management for smart grid applications

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HIGHLIGHTS

- A fast power demand response strategy involving cold storages is presented.
- Immediate and significant power demand reduction can be provided by the strategy.
- The life-cycle cost saving potential of cold active storage is analyzed.
- Small scale active storages can offer significant life-cycle cost saving.

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ABSTRACT

A fast power demand response (DR) strategy involving both active and passive cold storages is presented. This control strategy provides an immediate and stepped power demand reduction through shutting chiller(s) down when requested. The results show that the power demand reduction and building indoor temperature during the DR event can be predicted accurately. The power demand reduction is stable which is more predictable for the grid management. The building indoor temperature rise is restrained and indoor thermal comfort is improved through use of a small scale active storage system during the DR event. The incentive bought by an existing DR program is used to calculate the economic benefit of the demand reduction controlled by the developed fast DR strategy. In addition, an electricity price structure in South China is introduced to calculate the cost saving potentials of the active storages, when a storage-priority control is used to shift peak demand in normal days. The results show that small scale active storages can also offer significant life-cycle cost saving for building demand management.

1. Introduction

1.1. Background of research

The integration of large amounts of renewable generation, whose outputs depend heavily on weather conditions, e.g. solar density, wind speed, would cause significant stress on the balance of electricity grids. Any significant power imbalance might cause serious frequency problem. If the frequency fails to be recovered on time, grid may even suffer failures. In order to address these issues, smart grid with new characteristics, e.g. energy efficiency, low emission, flexibility, reliability, high quality, security and cost-effective, has been considered as a promising solution for future grid in plans of many countries. Smart grid enhance the power balance by improving the communication ability of involving different participants such as power suppliers, delivers and consumers through the smart grid control center. The smart grid control center is responsible for the information and communication managements including data and information collection, reliability and performance analysis, generation management and optimal control, as well as market and network operation arrangements. Demand Response (DR) programs are increasingly promoted to encourage power consumers to voluntarily alter or reduce the level of instantaneous demand in short time by providing time-based pricing or economic incentives. For instance, DR programs published by Regional Transmission Operators (RTOs) or Independent System Operators (ISOs) [1] often give customers load reduction incentives that are separate from, or additional to, their retail electricity rate, which may be fixed (based on average costs) or time-varying. The load reductions are needed when the grid operator thinks reliability conditions are compromised.

Some RTOs and ISOs, such as Midwest ISO, New York ISO (NYISO), ISO New England (ISONE), have allowed demand response

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resources (DRRs) to provide ancillary services [1]. Ancillary services are those functions performed by the equipment and people that generate, control and transmit electricity in support of the services of generating capacity, energy supply and power delivery. These services are required to maintain a balance between generations and loads in near real-time [2]. Traditionally, generators have dominated supplying ancillary services through injecting power to the grids. The ancillary services include regulating reserve, spinning reserve, non-spinning reserve, replacement reserve,etc. They are distinguished by the required response speed, duration, and frequency of deployment. For instance, the regulation reserve provides the continuous minute-to-minute balancing of generation and load under normal conditions. Spinning reserve is required to respond to event immediately and must fully respond within ten minutes. Non-spinning reserve does not need to respond immediately but is still required to fully respond within 10 min. Replacement reserve begins responding in 30–60 min.

Because reliability rules typically require the DR resources to be capable of supplying fast response, e.g. spinning reserve resources must deliver full capacity within 10 min and sustain their response for two hours. These DR programs are targeted to fast respond to specific reliability events with few hours, rather than reducing peak power demand over multiple hours [3]. In addition, accurate prediction of demand reduction is another requirement of IROs/ISOs [4]. Accurate prediction allows the IROs/ISOs to schedule electricity supply effectively to meet demand and to understand the characteristics of different DRRs.

Buildings are a major contributor to peak demand and play an important role in smart gird, while the largest portion of energy use in buildings is for the provision of heating, ventilation and air conditioning (HVAC), which accounts for around 50% of whole building energy consumption on average [5]. The HVAC systems can be an excellent DRR to supply ancillary reserves for several reasons [6]. First, HVAC systems contribute the largest portion of electricity consumption in commercial buildings. Second, the operation of HVAC systems normally can be temporarily curtailed without immediate and significant impact on building occupants. Third, the DR capacity of HVAC load can match the fast, short, less frequent requirement of ancillary reserves. The following part introduces the existing HVAC DR strategies and the performance investigation of the ancillary services provided by HVAC systems.

1.2. Literature review

Building thermal mass (BTM), as the main type of passive cold storage, can significantly affect the building cooling load due to their considerable capacities and resistances that may cause the reduction and delay of the external heat fluxes. The charging and discharging control of BTM, i.e. pre-cooling and global temperature adjustment strategies, are the most popular HVAC DR strategies. Global temperature adjustment is done by increasing building zone temperature set-points during the DR event [7]. Xu and Haves [8] 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 showed that a simple demand-limiting strategy could reduce the chiller power. Yin et al. [9] proposed the pre-cooling strategies optimization procedure for buildings with the demand response quick assessment Tool (DRQAT). A series of simulations were conducted to identify the optimal pre-cooling strategies with the calibrated simulation models. The "pre-cooling with exponential temp set up" and "pre-cooling with step temp set up" strategies turned out to be better DR strategies compared to the "Pre-cooling with linear temp set up" strategy. The predicted average demand shed during the DR event by DRQAT matched well with the measured data during the Auto-DR event days in the 7 of 9 field test buildings. The indoor thermal comfort is one important issue for the pre-cooling control. In order to further investigate the effects of pre-cooling on the building indoor thermal comfort, a web-based comfort survey was conducted by Xu et al. [10] in the field tests of two large scale commercial buildings with heavy mass. The results indicated that the occupant comfort was maintained in the pre-cooling periods and the following discharging periods.

A number of research studies were also conducted to investigate the performance and effects of ancillary services provided by the HVAC systems. How ancillary services can be obtained by using the power demand flexibility in HVAC systems was described by Hao et al. [11]. The building thermal and power consumption of HVAC system models were constructed. The control objective is to control the fan power tracking the time-varying signal. The results show that 15% of fan power capacity can be provided for regulation services while maintaining indoor temperature deviation no more than ±0.2 °C. Kiliccote et al. [12] conducted a pilot project to investigate the performance of DR in buildings which participated in wholesale ancillary services market. A DR strategy utilizing building indoor temperature set-point adjustments was used. During the DR period, the forecasted target demand shed was submitted to the ISO as available resource. Kiliccote [13] set out one demonstration to determine whether the HVAC systems could deliver DR that met the requirements of non-spinning reserves in California. Four DR strategies, each indicating a global temperature adjustment method, were conducted. The power demand during DR event was forecasted and compared with the measured power demand. It was found that the accuracy of the forecasted power demand influenced the accuracy of the delivered DR.

1.3. Motivation and research objective

The above studies show that DR measures from the power consumers can achieve power reduction when requested by smart grids. However, in the case that the DR is required to be activated in minutes, the existing HVAC DR strategies, such as global temperature adjustment, normally are difficult to provide quick enough DR to meet the requirements of fast power reduction (or ancillary services). These strategies could not reduce the power consumption of HVAC systems immediately because of the inevitable delays caused by the thermal mass of buildings [14] and the dynamic control process. Normally, it may take more than 20 min to generate obvious power reduction after building indoor temperature set-point is increased.

This paper therefore presents a fast power DR strategy for buildings by limiting the instantaneous capacity of chillers. Certain number of operating chiller(s) is shut down at the beginning of the DR event to achieve a significant and immediate power reduction. In order to enhance the capacity of power reduction or to provide additional cooling capacity for improving indoor thermal comfort level, an active cold storage system is introduced in the HVAC system. Three major innovative aspects are involved in this study. First, the usage of active storage system in HVAC system for the DR is seldom studied in the existing studies. Second, models are developed for predicting the power reduction and the building indoor temperature profile during the DR period. Third, a quantitative analysis on the life-cycle cost saving potential of active storage is then conducted to facilitate the decision makers to evaluate the economic benefits of active storage for fast DR and peak load management comprehensively and effectively.

The following parts in this paper begin with a description of the proposed fast power DR strategy in Section 2. The simulation test platform and test conditions are then described in Section 3. In Section 4, models coefficients identification and validation is conducted. It is followed by the case studies and analysis in