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Evaluation of a fast power demand response strategy using active and passive building cold storages for smart grid applications ☆

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ABSTRACT

Smart grid is considered as a promising solution in improving the power reliability and sustainability where demand response is one important ingredient. Demand response (DR) is a set of demand-side activities to reduce or shift electricity use to improve the electric grid efficiency and reliability. This paper presents the investigations on the power demand alternation potential for buildings involving both active and passive cold storages to support the demand response of buildings connected to smart grids. A control strategy is developed to provide immediate and stepped power demand reduction through shutting chiller(s) down when requested. The primary control objective of the developed control strategy is to restrain the building indoor temperature rise as to maintain indoor thermal comfort within certain level during the DR event. The chiller power reduction is also controlled under certain power reduction set-point. The results show that stepped and significant power reduction can be achieved through shutting chiller(s) down when requested. The power demand reduction and indoor temperature during the DR event can be also predicted accurately. The power demand reduction is stable which is predictable for the system operators.

1. Introduction

1.1. Background of research and literature review

Ancillary services are those functions required to maintain a balance between generations and loads in near real-time [1]. The ancillary services include regulating reserve, spinning reserve, non-spinning reserve, replacement reserve and etc. They are distinguished by the required response speed, duration, and frequency of deployment. Traditionally generators have dominated supplying ancillary services through injecting power to the grids. Some Regional Transmission Operators (RTOs) or Independent System Operators (ISOs), such as Pennsylvania–Jersey–Maryland (PJM), Midwest ISO, New York ISO (NYISO), ISO New England (ISO-NE) and etc., have already allowed demand response resources (DRRs) to participate in the ancillary service markets [2]. Demand response (DR) means a reduction of the electricity consumption of customers in response to an increase of electricity price or to incentive payments designed to induce low electricity consumptions. It balances the shortages by reducing demand rather than by increasing supply. As required by the reliability rules, the DRRs with control devices are capable of supplying fast response to specific reliability events with few hours, e.g. spinning reserves resources must deliver full capacity within 10 min, ramp and sustain their response for two hours [1]. Accurate prediction of demand reduction is also desired for IROs/ISOs to schedule electricity supply to meet demand [3].

Buildings consume about 73.6% of all electricity in the United States [4] and over 90% of all electricity in Hong Kong [5]. They can play an important role in DR programs by actively reducing their power consumption during peak hours. The heating, ventilation and air conditioning (HVAC) systems, which account for 50% of the whole building power consumption on average, are the main contributor for demand response in buildings. There are several reasons why the HVAC systems can be an excellent demand response resource to supply ancillary reserves [6]. First, HVAC systems contribute the largest portion of consumption in buildings. Second, the operation of HVAC systems can be curtailed or the equipment can be partially shut down without producing serious impact on building occupants [7]. Third, this DDR does not have ramping time, minimum on or off time limits that constrain many generators. The curtailment can be nearly instantaneously which is much faster than the 10 min allowed for generators to fully respond [8].

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Two main categories of DR strategies for HVAC systems were summarized by Watson et al. [9], which are global temperature adjustment plus precooling and cooling system adjustment. Global temperature adjustment is done by increasing building zone temperature set-points during the DR event. Cooling system adjustment includes duct static pressure setpoint reduction, fan quantity reduction, chiller quantity reduction and etc.

A number of research studies were also conducted to investigate performance and effects of ancillary services provided by the HVAC systems. Hao et al. [10] described how ancillary services could be achieved by the curtailment of power consumption of HVAC systems. The fan power tracking the assumed time-varying signal was the control objective after constructing the HVAC system and building thermal models. The results show that the frequency regulation could be offered if the fan power was modified within a small range, e.g. 10%, of its nominal power without noticeable impacts on the indoor environment. The performance of demand response in buildings which participated in wholesale ancillary services market was investigated in a pilot project [11]. A DR strategy utilizing 4° F temperature setpoint adjustments with one degree increment was adopted. During the DR period, the forecasted target demand shed and the actual demand shed were compared and the temperature set-points adjustments were accordingly made. Another demand response spinning reserve demonstration was carried out [12]. The magnitude of the demand shed of HVAC system was set as a function of time of day and expected weather conditions. The method of forecasting response had a confidence level of greater than 95% and an accuracy of greater than 90%. One study show that around 60% of the total 44 buildings could shed their power demand within 15 min once global temperature adjustment strategy was employed at the start of DR event [13]. A novel air-conditioning system with proactive demand control for daily demand shifting and real time power balance in the developing smart grid was proposed by Yan et al. [14]. The simulated integrated system consisted of a chilled water CTES together with a temperature and humidity independent control (THIC) air-conditioning systems, which could effectively enable a building with flexibility in the changing its power consumption patterns. Two types of demand response strategies, e.g. demand side bidding (DSB) strategy and demand as frequency controlled reserve (DFR) strategy, were implemented in respond to the day-ahead and hour-ahead power change requirements of the grid, respectively. A case study was conducted in a simulation platform to demonstrate the application of the proposed system in an office building. The results show that considerable energy and cost saving could be achieved for both the electricity utilities and building owners.

1.2. Research gaps and research objective

However, the above HVAC DR strategies normally cannot provide fast enough power demand reduction during DR events in response to the sudden electricity price rise or urgent grid reliability problems. Therefore, these strategies may fail to meet the requirements of ancillary services. The delays caused by the control process and building thermal mass usually restrain the demand response speed.

Therefore, a fast power demand response strategy with combined use of building passive and active cold storages is developed in this study. Certain number of operating chiller(s) is shut down at the beginning of the DR event to generate a significant and immediate power reduction in this developed strategy since the chillers are the largest power consumers in an entire HVAC system. Accurate demand reduction and indoor temperature prediction methods are also developed. The building indoor temperature rise is limited to avoid sacrificing the indoor thermal comfort too much as more cooling capacity provided by the active storage system. The minimum power reduction in the DR event is also controlled under certain demand reduction set-points. The DR effectiveness of the strategy involving both passive and active cold storages is evaluated by a set of introduced parameters.

2. Fast power demand response strategy for active and passive building cold storage

The number of operating chillers needed to be shut down is calculated based on the power demand reduction requirement in advance [15]. The corresponding allowable duration of demand response is also obtained before implementation of the developed fast power demand response strategy.

The flowchart of the proposed strategy is shown in Fig. 1. The DR strategy includes two parts to conduct the fast demand response in two steps. One is prediction step and the other is control step.

At Step 1, the predicted chiller power reduction and building indoor temperature are calculated based on the models. More importantly, the required active storage discharge rate, which is used to limit the building indoor temperature rise and control chiller power reduction under certain set-points during the DR event, is also acquired. The following modules and procedure are used:

- Chilled water temperature prediction module (Module 1): The supply chilled water temperature of overloaded chillers (T_{sup}) at the current sampling time is calculated by a polynomial function of return chilled water temperature (T_{rtn}) at the last sampling time. The return chilled water temperature at the current sampling time is then calculated based on the building cooling demand (Q_{dem}). Q_{dem} at the current sampling time and return chilled water temperature at the last sampling time are the inputs which are predicted in the last sample time.
- Building indoor temperature prediction module (Module 2): The building indoor air temperature (T_{in}) is obtained by solving the function of T_{sup}. As one of the most important parameters to indicate the indoor thermal comfort level, the building indoor temperature is required to be predicted. More importantly, the building indoor temperature rise should be limited to maintain the indoor thermal comfort within certain level. Actually, many factors affect the building indoor temperature. For facilitating the calculation process of the whole system, the building indoor temperature is represented by a simplified polynomial function of supply chilled water temperature when the remaining operating chiller(s) is overloaded after certain number of operating chiller(s) is shut down.
- Building indoor temperature comparison procedure: If T_{in} at the current sampling time is larger than the upper limit set-point of indoor temperature (T_{set}), T_{in} at the next sampling time will be set to a lower value ($T_{in,dis}$), shown in Eq. (1), through activation of the active storage system to decrease the return chilled water temperature.

$$T^{k+1}_{in,dis} = T_{set} \tag{1}$$

- Return chilled water temperature prediction module (Module 3): Similar to the building indoor temperature prediction module, the supply chilled water temperature is also represented by a simplified polynomial function of building indoor temperature. The return chilled water with decreased temperature ($T_{rtn,dis}$) at the current sampling time is then predicted based on the predicted supply chilled water temperature ($T_{sup,dis}$) at the next sampling time.
- Prediction of building indoor temperature using Module 1 and Module 2: Similar to Module 2, the building indoor temperature at the next sampling time is predicted based on the predicted