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Dynamic frequency regulation resources of commercial buildings through combined building system resources using a supervisory control methodology

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ABSTRACT

Frequency regulation (FR) is the electric grid service responsible for maintaining the system frequency at its nominal value of 60 Hz in the United States — an indicator of energy balance on the grid. In cases of mismatch between power supply and demand, FR resources either on the generation or the demand side, responding rapidly to restore system frequency to its nominal value. Due to the limited responsiveness of generators, fast and accurate demand side resources (DSR) have recently been encouraged to participate in FR. However, the tested DSRs typically require high initial equipment investment (e.g., flywheels and batteries). Large commercial buildings can provide effective load shaping with little impact to occupants' comfort and have significant amount of available capacity for FR participation. In addition, commercial buildings are characterized by numerous interdependent HVAC subsystems and control systems. Therefore, a high-level supervisory control strategy is needed that directs the interdependent HVAC systems for FR with strengthened interactions and depressed counteractions. Simulation results suggest that large commercial buildings can provide significant FR capacity and high performance scores. Dynamic building-to-grid integration automatically and continuously provides solutions maintaining energy balance on the gird. The benefit to the power system reliability would be significant.

1. Introduction

Frequency regulation (FR) is the key ancillary service for frequency control in order to maintain the energy balance on the electric grid. FR provides continuous, rapid, and automatic corrections that tracks small-scale demand variations and corrects unintended fluctuations of supply on a second-to-second basis [1]. If the demand is greater than the supply, the frequency drops below the target value (i.e., 60 Hz in the U.S.); if the demand is less than the supply, the frequency rises above the target value [2]. Frequency rate of change is determined by the inertia of all generators and rotating loads on the grid [2]. The frequency must be strictly maintained within a very narrow range in order to comply with the control performance standards (CPS) and the balancing authority ACE Limit (BAAL) reliability criteria [3]. Traditionally, FR is supplied by directing dedicated generators in response to a signal sent by the independent system operator (ISO) or the regional transmission organization (RTO). In recent years, however, three types of DSRs have emerged that increasingly participate in the FR service [4]. (1) Grid-scale storage, such as flywheels, batteries,

Abbreviations: ACE, area control error; AGC, automatic generation control; AHU, air-handling unit; BAAL, balancing authority ACE limit; BAS, building automation system; CPS, control performance standards; DR, demand response; DSM, demand side management; DSR, demand side resources; EcoBasepoint, building baseline power consumption; FERC, Federal Energy Regulatory Commission; FR, frequency regulation; HVAC, heating, ventilating and air-conditioning; ISO, independent system operator; MPC, model predictive control; PBR, performance based regulation; PJM, Pennsylvania–New Jersey–Maryland interconnections; PL, participation level; PSC, performance score calculation; RegA, traditional regulation signal; RegD, dynamic regulation signal; RES, renewable energy sources; RMCCP, regulation market capacity clearing price; RMPCP, regulation market performance clearing price; RTO, regional transmission operator; SPWM, sinusoidal pulse width modulation; TReg, total regulation capacity; VAV, variable air volume; VFD, variable frequency drive.

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compressed-air energy storage (CAES) and pumped-hydro; these resources do not generate electricity as generators do but can draw and store electricity from the grid and then release it when needed [5–7]. (2) Heating systems, such as electric boilers and resistance heaters; these resources vary the heater electric consumption (i.e., adjusting the heating capacity) in response to the FR signal [8]. (3) Independent systems with variable frequency drives (VFD), such as wastewater treatment pumps and supply fans in air-handling units (AHU); these resources vary the motor electric consumption (i.e., adjusting the motor rotating speed) in response to the FR signal [9,10]. These three types of resources typically have smaller capacity than generators but can ramp much faster and respond to the FR signal more accurately and thereby offer better performance. In October 2011, the U.S. Federal Electric Regulatory Commission (FERC) issued the final rule of Order 755, which directs the ISOs and RTOs to evaluate and compensate FR services provided based on resources' actual performance instead of their expected FR capacity [11]. The Pennsylvania-New Jersey-Maryland (PJM) RTO launched their performance-based regulation (PBR) rule in October 2012 in response to FERC order No. 755. This rule compensates FR resources based on two parts of offers, capacity and performance, that are market-based and derived from bidding offers with uniform clearing price [12,13]. In July 2013, FERC launched Order No. 784 [14]. This rule further expands upon Order 755 and emphasizes the accuracy and speed of FR resources [14].

Large commercial office buildings are equipped with flexible, often thermostatically controlled loads (e.g., air-conditioning systems, heating systems and water heaters), VFD-controlled motor loads (e.g., supply fan, return fan and chillers) and lighting loads. These loads are able to adjust their power consumption along with the dynamic FR signal and thus provide commercial buildings with the potential to participate in FR [4,10,15]. This paper intends to explore the quality of response and the potential incentive received by manipulating a commercial HVAC system for FR. The typical approach to integrating building operations for grid reliability is through demand response (DR) programs in the energy market. Commercial buildings shed loads during critical periods and receive financial incentives for the amount of load shed or for simply being available. However, building managers usually found a lack of transparency in the energy markets for the energy cost and benefits analysis [17]. Energy consumption rebounds are typically found right after DR events so that DR programs are about load shifting and short-term shedding but not about energy efficiency or energy saving [18,19]. In addition, the rebound creates a new peak that is problematic for the energy balance and impacts grid reliability. In contrast, emerging DR programs aim at continuously integrating end-users in ancillary services, such as FR and spinning reserve [4,19,20]. The supervisory control method developed in this paper dynamically integrates building operations into grid operations as a FR resource that responds to mismatches in supply/demand in real-time. If a bundle of buildings is controlled for FR, significant levels of available capacity can effectively increase grid reliability and alleviate power transmission congestion. Unlike traditional DR programs that engage only sporadically during times of grid stress, dynamic building-to-grid integration automatically and continuously provide solutions from the demand side maintaining energy balance on the grid. The benefit is expected to go beyond traditional DR programs.

This paper is organized in the following sections: Section 2 presents a literature review and relevant background information. Section 3 describes the methods of modeling a commercial HVAC system and its low-level controls for baseline evaluation. Section 4 introduces four FR signal injection methods and a supervisory control method. Section 5 presents and evaluates the simulation results and provides an analysis of the results. Section 6 summarizes the conclusion.

2. Literature review

Electricity supply is provided by many sources of diverse technologies in order to track the aggregated load profile throughout the day. In the absence of effective grid-scale storage, electricity must be generated, distributed and consumed in real time. This poses a challenging task for the grid operators to dispatch vast amounts of power from various sources to meet the substantial variations from load valleys to load peaks on any day. In addition, renewable energy sources (RES), such as wind and solar, are increasingly introduced to the grid. These sources are intermittent, variable and introduce more volatility to grid operations at higher levels of penetration [21,22,25]. Aside from balancing generation and load through economic dispatch on an hour-to-hour basis, grid operators also face small-scale levels of mismatch of generation and load that require FR on second-to-second basis. FR is a "zero electric energy" service because of the symmetrical responses toward positive and negative directions; thus, the integral value of a FR resource's electric power output is zero. Nonetheless, it does require significant amounts of fossil fuel input if provided by generators. Research estimated that integrating RES at the current pace would exceed both of the ramping rate and capacity of traditional FR resources' ability to compensate [23,24]. Thus, DSR participation presents an attractive avenue for energy efficiency improvement in balancing generation and load. A recent report found that an ideal FR resource (i.e., unlimited capacity and instant response) can be two times more efficient than traditional resources in general [26]. Thus, dynamic DSRs are encouraged to participate in FR [11,12]. The result of incorporating dynamic DSRs has already shown significant benefits after the PBR rule's being in operation during its first year. System reliability was improved as measured by improved CPS and BAAL scores with FR requirement kept constant [27]. Thus, it was suggested that FR requirements can be lowered in order to determine the impact on system reliability by allocating less FR resources [27]. PJM lowered the requirement from 1.0% of total generation for FR to 0.7% (total generation in PJM is approximated from 80,000 MW valley load to 140,000 MW peak load) [27,28]. In spite of this significant change in FR requirements, CPS and BAAL scores remained high and even increased in summer months [27]. Thus, incorporating dynamic FR resources proved to increase the energy efficiency on the entire power system.

The thermal mass inherent in commercial buildings, such as concrete, drywall, and furniture can be used to manipulate heating and cooling loads. Utilizing thermal mass for load shifting and cost reduction has been successfully implemented in commercial buildings in the summer season and is known as pre-cooling [30]. This has shown significant effect on peak load and cost reduction [17,29,30]. Typically, a high-level optimal control is needed to properly harness the thermal mass storage for maximum benefit such as cost savings [31–33,36]. A recent study proposed a model predictive control (MPC) framework to determine the optimal operating strategy considering energy cost, peak demand and FR revenue through simulations based on PJM's rules and pricing data [34].

As building thermal mass has demonstrated to be an effective grid-scale storage, we argue that commercial building HVAC systems can provide FR similar to other prevailing storage devices such as batteries and flywheels while maintaining occupants' comfort. However, the question arises, whether a commercial building is ramp-limited or a capacity-limited resource? According to PJM's PBR rule, the signal RegA is designed for ramp-limited resources that are typically rich in FR capacity but ramp slowly [35]. In contrast, the signal RegD is designed for capacity-limited resources that feature typically less available capacity but ramp quickly [35]. Therefore, the question can be paraphrased as: "Are commercial building HVAC systems a RegA-following or a RegD-following resource"? The answer is both, depending on the number of