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Multi-time scale coordination of complementary resources for the provision of ancillary services[☆]

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HIGHLIGHTS

- A methodology to offer frequency regulation with complementary resources is presented.
- Their aggregated flexibility is formally computed.
- An experimental campaign is conducted on an office building and an electrical battery.
- Results reveal that combining such resources increases the offerable flexibility.
- Excellent tracking performance can be achieved while respecting all local constraints.

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ABSTRACT

This paper presents a predictive control scheme for coordinating a set of heterogeneous and complementary resources at different timescales for the provision of ancillary services. In particular, we combine building thermodynamics (slow), and energy storage systems (fast resources) to augment the flexibility that can be provided to the grid compared to the flexibility that any of these resources can provide individually. A multi-level control scheme based on data-based robust optimization methods is developed that enables heterogeneous resources at different time scales (slow and fast) to provide fast regulation services, especially a secondary frequency control service. A data-based predictor is developed to forecast the future regulation signal and is used to improve the performance of the controller in real-time operation. The proposed control method is used to conduct experiments, for nine consecutive days, demonstrating the provision of secondary frequency control fully complying to the Swiss regulations, using a controllable building cooling system on the EPFL campus and an emulated grid-connected energy storage system. The experimental results show that optimally combining such slow and fast resources can significantly augment the flexibility that can be provided to the grid. To the best of author's knowledge, this work is the first experimental demonstration of coordinating heterogeneous demand-response to provide secondary frequency control service.

1. Introduction

In proportion to the total amount of electricity that is produced and consumed, very little energy storage capacity is available across the power grid. As a consequence, production and consumption of electricity must practically be balanced at all times across any power network. However, due to inherently unpredictable fluctuations, imbalances between the two are always present and need to be compensated in real-time to preserve the system frequency at its rated value (50 Hz in Europe) and, by doing so, prevent blackouts or the need to shed loads or generators from the network. This is typically achieved by keeping a set of power reserves on standby and ready to absorb any deviation. Depending on regional terminology, these reserves are called ancillary service providers (ASP), spinning reserves or operating reserves [1,2]. These power reserves historically have been provided mainly by highly responsive power plants such as hydro-power plants,

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gas or coal stations, etc. However, utilizing these type of resources presents both economic and environmental issues [3]. Economic issues come from the fact that, in order to be able to respond to the network's need, ancillary reserves run at operating points that are not economically optimal, for example at part load. This incurs a loss-of-opportunity cost for ancillary reserves operators, for example, a revenue deficit if a power plant runs at 90% of its full capacity, or conversely an excess cost when the power plant has to run while the market price of electricity is too low to cover the price of fuel. Environmental issues are due to the fact that fuel-based power plants are kept running as spinning reserves even when abundant renewable production is available. In addition, the increasing penetration of uncertain and uncontrollable sources of energy production such as solar and wind power has caused an increase in unpredictability and volatility of energy production.

It is therefore of paramount importance to integrate into the system new type of resources to improve the overall cost-efficiency of the power network. Potential candidates could be represented by, e.g., Electrical Storage Systems (ESS) or thermal storage systems by controlling the Heating, Ventilation and Air conditioning (HVAC) of large commercial buildings. ESSs are very well suited for ancillary services since they are highly controllable devices that exhibit very fast ramp rates [4]. In a landscape where the overall rotational inertia of the grid is decreasing, having such fast-responding ASPs could help to reduce the frequency deviations and, thus, better stabilizing the operation of the electric grid [5]. However, the main challenge when proving Ancillary Services (AS) with ESSs is represented by the management of the State of Charge (SoC) level. In fact, the control signal to be tracked can exhibit significant biases over prolonged periods of time which can rapidly lead to the complete charge or discharge of the ESS. For this reason, in recent years different recharging strategies have appeared to optimize the provision of fast regulating services. In [6] an off-peak-hours recharging strategy was considered that manages the SoC tapping the available capacity of conventional generators. Oudalov et al. [7] utilize a deadband around nominal system frequency to adjust the SoC. Borsche et al. [8] propose a moving-average strategy to compensate for imbalances in the regulation signal, and efficiency losses in the storage system. This continuous adjustment is summed to the received tracking request in order to obtain the final power setpoint to the battery. The strategy was successfully tested both in simulation [8], as well as on the grid-connected Zurich 1 MW electric battery [3,9], that was used for different grid applications. All these studies typically focused on primary frequency control due to the smaller energy throughput that is typically required with respect to, e.g., Secondary Frequency Control (SFC). Nevertheless, due to the worst-case energy requirements and/or the conservative prequalification rules recently implemented by many Transmission System Operators (TSOs), even in this case, ESSs do not represent, in general, an economically viable solution due to very large capital costs [9].

On the other hand, the potential of demand-side resources to offer control reserves has been extensively recognized by both the academic and industrial community [10]. Buildings are responsible for 40% of the total energy consumption worldwide with a roughly equal share for residential and commercial buildings [11]. Moreover, buildings are inherently characterized by a large thermal inertia that can be used to store large amounts of energy in the form of thermal energy. In particular, commercial buildings are good candidates for providing services to the grid for the following reasons: (1) they are typically characterized by a large HVAC system with respect to residential buildings. This corresponds to larger energy consumption per unit which in turn means a smaller cost of acquisition. (2) Many commercial buildings are already equipped with a Building Energy Management Systems (BEMS) that can be readily used to monitor and control the operation of their HVAC systems [12].

For these reasons, in the recent years several theoretical, simulation-based and experimental contributions have appeared studying the potential of commercial buildings to provide ancillary services to the grid. In [13], De Coninck et al. present a cost curves based-approach to quantify the amount of flexibility a building can offer together with its associated cost. Rather than on the planning and real-time phases, the method focuses on the design process and provides an approach to select the most promising buildings to include in the DR scheme. A similar effort was made in [14] where a methodology was proposed to obtain a flexibility function that can be used to label energy flexible systems such as buildings.

Several theoretical works have proposed frameworks to compute the tracking capabilities of controllable loads such as commercial buildings. These methods are typically model-based and leverage robust programming techniques. In particular, [15] describes a Model Predictive Control (MPC) strategy, in a single-input setting, to formally determine the deviation that a building can sustain around a pre-specified baseline. A more general approach, that can handle the multi-input case, was introduced in the recent contributions of [16,17]. In [18] and the follow-up works [19,20], a hierarchical control framework to coordinate the aggregation of a set of office buildings was proposed.

Another line of research focuses on the practical feasibility of actually deploying both simple and advanced strategies to reliably provide SFC using the HVAC systems of commercial buildings. In fact, due to their inherent complex nature with multiple cascade control loops, self-correcting behaviors, and physical limitations of the equipment, the power consumption of a standard HVAC systems cannot, in general, be modulated reliably and at a very high-frequencies. To mitigate this problem, several approaches have been proposed that typically focus on identifying specific HVAC components that can sustain such fast power changes. In [21], Su et al. propose a practical control framework to track a filtered version of the Automatic Generation Control (AGC) signal for secondary frequency regulation. This is achieved by acting on the chilled water supply setpoint of a chiller which, in turn, has a quantifiable effect on the electric power consumption of the HVAC system. A similar approach was also considered in [22,23] where the power tracking was provided by adjusting the fan power consumption of the main air handling unit through either direct fan speed offset or by adjusting the mass flow setpoint. Also in this case, the building receives a filtered version of the AGC that is tracked in a [1/30 s to 1/1 min] or [1/1 min 1/10 min] frequency band, depending on the considered configuration. In the same direction, a more extensive experimental study is represented by [24] where Vrettos et al. analyze the potential of offering frequency regulating by modulating the fan power via speed control. The study includes also a formal computation of the regulation capacity that can be offered by the building. Experiments were made in single-zone unoccupied test cells equipped with a standard cooling system. The conclusion of the aforementioned papers, also confirmed in the extensive simulation studies [25,26], is that controlling fast-responding Air Handling Unit (AHU) fans by means of either speed offset, or supply pressure/mass flow setpoint, could guarantee tracking performance in line with the typical TSO's requirements. However, despite their fast response rates, these methods have also some drawbacks. First, direct control of fan speed is not readily possible in many BEMS [27]. Thus, this would require some level of retrofitting adding cost and complexity. Moreover, due to the complex control architecture of commercial buildings, slower control loops will likely compensate for net changes to supply pressure of mass flow which limits the ability of these strategies to track reference signals with slow time-scales. A different approach has been proposed in [28,29,27], where authors propose to track the reference signal by adjusting the thermostat setpoint offset which has an indirect effect on the fan consumption through the corresponding change in the room damper and, therefore, the mass flow pressure. The advantages and disadvantages of this method are opposite of the previous ones [25]. In general only software modifications would be required since thermostat changes can be done through many BEMS. However, since the electric power of fans is only controlled indirectly, communication and mechanical latency can significantly impact the tracking performance [27].