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Optimizing commercial building participation in energy and ancillary service markets

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ABSTRACT

Providing ancillary services through flexible load response has the potential to increase electric grid reliability and efficiency while offering loads a revenue generating opportunity. The large power draw of commercial buildings, along with thermal mass characteristics, has sparked interest in providing ancillary services through intelligent operation of building mechanical systems. As a precursor to participating in ancillary service markets, the quantity of service available must be estimated. This work presents a model-based approach for estimating commercial building frequency regulation capability. A model predictive control framework is proposed to determine optimal operating strategies in consideration of energy use, energy expense, peak demand, economic demand response revenue, and frequency regulation revenue. The methodology is demonstrated through simulation for medium office and large office building applications, highlighting its ability to merge revenue generating opportunities with traditional demand and cost reducing objectives.

1. Introduction and motivation

Operating a reliable and effective large-scale electric power system requires the procurement and scheduling of resources over several time scales. Long-term planning secures the availability of adequate generation capacity to meet changing consumer needs, while short-term scheduling and dispatch activities ensure real-time stability through continuously balancing electricity supply and demand. In addition to the scheduling of generation capacity, various ancillary services, such as frequency regulation, spinning reserves, voltage control, and black start, are required to maintain power system reliability [1]. Frequency regulation ancillary service is responsible for correcting small deviations between supply and demand that occur on minute or sub-minute time scales, while spinning and non-spinning reserve services provide a safeguard against generator failures and contingency events.

Historically, demand resources have played a relatively inflexible role in energy and ancillary service markets, requiring grid balancing operations to be achieved solely through modulation of generating resources. However, response from flexible loads may be able to provide ancillary services in a more accurate, reliable, and prompt manner than traditional generation equipment which may ultimately reduce ancillary service requirements without compromising reliability [2]. Additional benefits of incorporating flexible load response into energy markets may also include: increased system reliability, improved market efficiency, risk management, reduced environmental emissions, market power mitigation, and increased system efficiencies [3].

For commercial buildings to participate in ancillary service markets it is necessary to estimate the quantity of service that is able to be provided. It is also necessary to develop operational strategies that optimally balance revenue generating opportunities with expense (or energy) reducing objectives (e.g. following a frequency regulation signal may increase peak demand if not planned carefully). In pursuit of integrating commercial building operation with energy and ancillary service markets, this work presents: (1) a model-based approach for estimating the hourly capability of a commercial building to participate in the regulation ancillary service market, and (2) a model predictive control (MPC) framework

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Nomenclature

C_c	external roof thermal capacitance
C_e	external wall thermal capacitance
C_f	floor thermal capacitance
C_i	internal thermal capacitance
C_p	air thermal capacitance
C_z	zone thermal capacitance
CHW	chilled water
e_k	transfer function heat gain history coefficient
E_{cost}	energy cost
E_{use}	energy use
$ElecDemand_{peak}$	electric demand during peak hours
FR	frequency regulation
h_{fg}	heat of vaporization of water
j, k, l	transfer function indices
J	optimization cost function
m	transfer function heat gain history order
m_{air}	mass of zone/building air
$\dot{m}_{\mathrm{inf}}$	infiltration mass flow rate
$\dot{m}_{SA}$	supply air mass flow rate
M	demand penalty slope
n	transfer function input series order
NSU	night time setup strategy
NSU+FR	night time setup strategy with frequency regulation estimation
OA	outdoor air
OPT	optimal strategy excluding frequency regulation
OPT+FR	optimal strategy including frequency regulation
P_{demand}	demand penalty
$q_{occ,lat}$	latent heat gain per occupant
$\dot{Q}_{g,c}$	convective portion of internal gains
$\dot{Q}_{g,r,c}$	radiative fraction of internal gains applied to ceiling surface
$\dot{Q}_{g,r,e}$	radiative fraction of internal gains applied to vertical wall surface
$\dot{Q}_{\mathrm{inf}}$	infiltration heat gain
$\dot{Q}_{sol,c}$	solar radiation transmitted through opaque ceiling/roof surfaces
$\dot{Q}_{sol,e}$	solar radiation transmitted through opaque vertical exterior surfaces
$\dot{Q}_{sol,w}$	solar radiation transmitted through glazing
$\dot{Q}_{sh}$	sensible convective heat gain to zone air
$\dot{Q}_{zs}$	sensible zone load
r_{DA}	day-ahead energy price (rate)
r_{reg}	regulation price (rate)
R_c	external roof thermal resistance
R_f	floor thermal resistance
R_i	internal partition thermal resistance
R_e	external wall thermal resistance
R_w	glazing thermal resistance
RA	return air
R_{reg}	regulation revenue
S_k	transfer function input coefficient vector
t	time or time index
T_a	outdoor air temperature
T_c	ceiling node temperature
t_{CH}	final time interval in cost horizon
T_e	exterior wall node temperature
T_f	floor node temperature
T_g	ground temperature
T_i	internal partition temperature
T_{SA}	supply air temperature
T_z	zone air temperature
TDL	target demand limit
$\overline{T}_z$	average zone air temperature over timestep
$\mathbf{u}_t$	transfer function input matrix
W_{OA}	outdoor air humidity ratio
W_{SA}	supply air humidity ratio
$\vec{x}$	control setpoint vector
δ	control setpoint perturbation
$\Delta\tau$	timestep
Δ_{power}	power change from from baseline

for optimizing commercial building participation in both energy and ancillary service markets.

2. Background

2.1. Vehicle-to-grid

Recent work towards grid integration of electric vehicles provides an important source of relevant literature. Intelligent charging algorithms for providing frequency regulation have been developed [4,5], as well as a methodology for scheduling both spinning reserves and frequency regulation [6]. An extension was also made to consider selling energy back to the grid (i.e. battery discharging), unexpected vehicle departures, and battery degradation costs due to cycling [7]. In general, formulations seek to determine a preferred operating point (i.e. baseline charging or discharging strategy) and the additional power draw limits that maximize the profits of the electric vehicle aggregator.

2.2. Commercial buildings

With respect to the building science domain, previous work has demonstrated that significant peak electric demand reductions can be achieved through utilizing building mass as a thermal storage medium [8–10]. Building energy simulation programs have been coupled with optimization routines in a MPC framework to determine zone temperature setpoint strategies that minimize building utility cost considering time-of-use electric rates and peak demand charges [11]. Real-time pricing scenarios have also been considered [12,13], creating a link between building operations and energy market pricing signals.

Aside from the benefits achieved through load shifting and price response, buildings with significant thermal mass may also be well-suited to provide ancillary services since zone thermal inertia can buffer intermittent or varied HVAC operation [1]. Residential air conditioners have been evaluated for providing spinning reserve services [14], and a pilot study successfully bid commercial building demand response into day-ahead non-spinning reserve markets [15].

Recent work has also considered controllable building electric loads for economic dispatch in energy markets. As an example, chilled water supply temperature was modified to create changes in electric demand [16]. Frequency regulation (FR) in commercial buildings through zone temperature and duct static pressure setpoint modulation has also recently been investigated [17]. An overview of the FERC Order 755 “pay-for-performance” rule, as implemented in PJM, was provided highlighting the opportunity for buildings to be compensated for faster and more accurate response to regulation dispatch. Detailed thermal zone and HVAC models were used to evaluate building response while tracking a FR signal. Similar work has also proposed combining the regulation signal with a variable speed fan control signal to directly modulate fan speed [18].