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Optimal use of thermal energy storage resources in commercial buildings through price-based demand response considering distribution network operation

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HIGHLIGHTS

- A DR framework is proposed to assist buildings in exploiting thermal energy storage.
- Thermal dynamics of an experimental building room with a VSHP are modelled.
- Operating conditions of distribution grid are considered for price-based DR of VSHPs.
- Two-stage optimisation problems are formulated considering wind power forecast error.

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ABSTRACT

Energy storage resources (ESRs) inherent in building structures are a viable, attractive option to improve power system operation by providing demand-side flexibility. This paper proposes a two-stage optimisation framework for price-based demand response of commercial buildings that include variable speed heat pumps (VSHPs). The proposed framework aims at assisting commercial building aggregators to devise a beneficial strategy for exploiting thermal ESRs in response to electricity prices. Specifically, in this paper, the thermal dynamics of VSHPs are modelled in detail using a set of piecewise linear equations for two different methods of room temperature control. The energy consumption and reserve provision of VSHPs, as well as plug-in electric vehicles, are then co-optimised considering the operating conditions of distribution networks (DNs) for the pre- and post-contingency states of wind power generation. Simulation case studies are performed to estimate the effects of building ESRs on the optimal operation of power systems and commercial buildings under various conditions characterised by: (1) temperature control methods, (2) ESR penetration levels, and (3) DN operational constraints.

1. Introduction

In many developed countries, buildings are one of the largest energy end-use sectors, accounting for a larger proportion of total energy consumption than industry and transportation sectors [1]. For example, in 2010, commercial buildings accounted for 35% of total electricity consumption in the United States (US) [2]. Thermal energy storage resources (ESRs) inherent in building structures are coupled to power systems through heating, ventilation, and air-conditioning (HVAC) systems, which represent approximately 30% of electricity usage in commercial buildings [3]. The energy storage capacity of building structures, as well as the development of associated power electronics, allows HVAC systems to be exploited as demand response (DR) resources that require moderate usage of communication systems for input power control. In particular, HVAC systems have been integrated into DR programs with time-varying electricity price mechanisms [4] to reduce occupant discomfort, building electricity bills, or power system operating costs.

Price-based DR has been widely studied, with and without consideration of various types of electricity market [5–16]. For example, in [5], a centralised market-clearing mechanism was proposed using the load shifting capability of consumers who submitted price-sensitive bids. A security-constrained market clearing algorithm was proposed in [6] using demand-side flexibility for spinning reserve provision. Iterative and non-iterative methods were also developed in [7] to examine the impacts of DR load levels on the market clearing prices. In [8], a DR program was incorporated into a real-time balancing market. However, the types or characteristics of the DR loads were not specified or modelled in

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Nomenclature

t, b, h, e, r	subscripts for time, a building, a VSHP, a PEV, and a building room
s	superscript for a wind power scenario
P_{ht}, Q_{ht}	power input and cooling rate of VSHP h at t
T_{rt}	indoor temperature for building room r at t
Q_{ct}, Q_{rt}	heat gains of convective and radiative internal loads for building room r at t
$F_{\mu hkj}$	linear gradient of T_{rt} at $t = j$ resulting from power block μ of VSHP h at $t = k$
$\delta_{\mu hk}$	power input of VSHP h in block μ at $t = k$
P_{et}	power input of PEV e at t
r^{Us}_{ht}, r^{Ds}_{ht}	upward/downward reserve provided by VSHP h at t and in scenario s
r^{Us}_{et}, r^{Ds}_{et}	upward/downward reserve provided by PEV e at t and in scenario s
N_T	number of scheduling time intervals in a day
N_s	number of scenarios of wind power forecast errors
N_H, N_E, N_R	total numbers of VSHPs, PEVs, and building rooms
N_{BH}, N_{BE}	numbers of VSHPs and PEVs in a building
N_{BUS}, N_G, N_D	numbers of TN buses, thermal generators, and loads
N_O, N_B	numbers of bidding blocks submitted by generator and consumer load
C^E_t, C^{Rs}_t	nodal marginal prices for energy consumption and reserve provision at t and in scenario s
$\Delta T^h_{rt}, \Delta T^l_{rt}$	high and low indoor temperature violations for building room r at t
$\boldsymbol{J}^{\theta V}, \boldsymbol{J}^{Ploss}$	Jacobian matrices of variations in voltage magnitudes and line power losses with respect to load variations throughout DN
$\boldsymbol{P}^{SB}_{Ht}, \boldsymbol{P}^{SB}_{Et}$	matrices of individual VSHP and PEV loads in price-sensitive buildings at time t
$\boldsymbol{P}^{CB}_{Ht}, \boldsymbol{P}^{CB}_{Et}$	matrices of individual VSHP and PEV loads in conventional buildings at time t
$\Delta\boldsymbol{V}_{mag,max}$	maximum allowable increments of voltage magnitudes at all DN nodes
$\Delta P_{loss,max}$	maximum allowable increments of total power loss in DN
u_{ht}	binary variable for operation of VSHP h at t
u_{gt}, v_{gt}, w_{gt}	binary variables for generator g to be committed, started-up, and shut-down at t
P^G_{gmt}, P^D_{dkt}	power scheduled in bidding block m of generator g and bidding block k of consumer d
P^W_{nt}	wind power output forecast at t and at TN bus n
P^B_{nt}	total VSHP and PEV load in price-sensitive and conventional buildings at t and at TN bus n
P^D_{dt}	load forecast of consumer d at t
$\gamma_{gmt}, \gamma_{dkt}$	prices for bidding block m of generator g and for bidding block k of consumer d at t
$r^{Gs}_{gmt}, r^{Ds}_{dkt}$	reserves deployed for bidding block m of generator g and for bidding block k of consumer d at t in scenario s
r^{Bs}_{nt}	reserve deployed by price-sensitive buildings at t and at TN bus n in scenario s
R^{GU}_{gt}, R^{GD}_{gt} R^{DU}_{dt}, R^{DD}_{dt}	upward/downward reserve capacities scheduled for generator g and consumer d at t
$r^{GUs}_{gt}, r^{GDs}_{gt}$ $r^{DUs}_{dt}, r^{DDs}_{dt}$	upward/downward reserves provided by generator g and consumer d at t in scenario s
C_o, C_{su}, C_{sd}	no-load, start-up, and shut-down costs of generator
$C^{RUD}_{gt}, C^{RUD}_{dt}$	offer costs for upward/downward reserve capacities of generator g and consumer d at t
S^{Ws}_{nt}	wind power spillage at t and at TN bus n in scenario s
M^n_G, M^n_D, M^n_L	set of generators, loads, and lines connected to TN bus n
B_{nv}	line susceptance between TN buses n and v
θ_{nt}, θ_{vt}	voltage angles at TN buses n and v
$prob_s$	probability for scenario s

these papers. In [9–16], thermal ESRs were specifically considered to determine optimal DR schedules mainly for operating cost minimisation. For instance, variations in the input power and cooling rate of HVAC systems were modelled in [9,10] to minimise the total cost of purchasing electrical power and natural gas. In [11], the on-off operations of electrical water heaters (EWHs) were modelled for a robust optimisation approach to reduce residential electricity bills. In these studies, the HVAC system models were simplified, for example, by assuming a constant or predetermined coefficient of performance (COP); however, this may not be consistent with the practical operation of an HVAC system. Rather detailed models of thermal ESRs were implemented in [12–16]. For example, the thermal dynamics of an EWH were modelled in [12] using the equivalent thermal parameter (ETP) method. The ETP approach was also adopted in [13,14] to describe the heat balance inside a residential building using first-order differential equations. In [15], a second-order equivalent model of a heat pump was implemented to optimise its power consumption considering the building thermal dynamics over discrete time intervals. For DR application to commercial buildings, additional attention should be paid to the use of an ETP model for analysing the thermal dynamics of commercial building rooms [17]. In [16], variable-air-volume (VAV) cooling systems in commercial buildings were comprehensively modelled to determine the optimal input power schedules without adopting the ETP approach. However, little analysis has been provided on the impacts of thermal ESRs on electricity markets or distribution networks (DNs) in [9–16]. As discussed in [18–20], the widespread adoption of building ESRs will introduce additional dynamics to power flows in the DNs through which ESRs receive energy and provide reserves to the electricity market. In addition, a DN infrastructure accommodates conventional loads, including critical loads such as healthcare facilities. Therefore, stable DN operation needs to be ensured in the implementation of price-based DR for thermal ESRs. This implies that DN operational conditions, such as voltage magnitude and line power loss, affect the energy and reserve schedules of building ESRs and, consequently, the electricity bills of buildings.

Based on these observations, this paper presents an optimisation framework in which commercial building aggregators (CBAs) minimise their operating costs by integrating building ESRs into the price-based DR program. It mainly aims to evaluate comprehensively the impact of thermal ESRs in commercial buildings on the operating cost of an independent system operator (ISO), as well as electricity market prices, based on comparative case studies. Specifically, in the proposed framework, CBAs determine the optimal schedules of energy consumption and reserve provision of thermal ESRs in response to electricity prices, while considering DN operational conditions, namely, voltage magnitude variation and line power loss. The ISO is informed of the CBAs' optimal schedules because the effects of the ESRs on the electricity price will be non-negligible as their penetration continues to increase. The thermal generators and consumer loads, which directly submit price-sensitive bids to the ISO, are then allowed to change their optimal schedules accordingly. This results in an updated electric-