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Optimal scheduling of aggregated thermostatically controlled loads with renewable generation in the intraday electricity market ☆

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HIGHLIGHTS

- A novel two-level approach is proposed to schedule aggregated thermal loads.
- Revenues for prosumers in the intraday electricity market are maximized.
- An energy-balanced model is established for aggregated scheduling.
- The imbalanced energy and capacity are considered to be reduced at the same time.
- The effects of imbalance prices, heterogeneity and forecast errors are studied.

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ABSTRACT

A novel two-level scheduling method was proposed in this paper, which helps an aggregator optimally schedule its flexible thermostatically controlled loads with renewable energy to arbitrage in the intraday electricity market. The proposed method maximizes the economic benefits of all the prosumers in the aggregation, and naturally helps balance intra-hour differences between supply and demand of the bulk power systems because the prices of the intraday electricity market reflects the need of the bulk power systems. In the proposed two-level scheduling, the upper level is a model predictive control optimization, of which the objective function is to minimize the sum of energy and capacity cost of imbalances and the constraints are thermal constraints based on a proposed energy-balanced model, while the lower level adopts the typical temperature priority list (TPL) control. Simulation results verified the validity of the proposed method and evaluated the effects of important influencing factors. In the base case, 41.64% imbalance cost was saved compared to the reference TPL-based control. Moreover, three further conclusions were drawn: (a) the proposed method mainly saves the imbalance cost by reducing imbalance peak, thus being suitable for places with high capacity price for imbalances; (b) parameter heterogeneity affects the performance of the proposed method, and average value method performs well only with low heterogeneity; (c) the performance of the proposed method worsens with the increase of forecast uncertainty, but keeps better than that of typical TPL-based control unless the forecast uncertainty gets very strong.

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1. Introduction

Renewable energy has been being developed rapidly all around the world during the latest decades, and its penetration in power systems keeps increasing. A large portion of renewable energy is being deployed at the household level in the forms of rooftop photovoltaic arrays and small wind turbines, which makes many residential consumers become "prosumers" that are also able to produce electricity. In spite of various contributions to environmental conservation and sustainable development, renewable energy of high penetration presents great challenges to power systems due to its serious randomness and variability, resulting in significant demand for operating reserves. Traditional large centralized regulating generators are not considered to be an ideal solution because increased ramp and capacity requirement would lower the efficiency, shorten the lifetime and increase the wear-and-tear cost of the generators. In contrast, flexible demand

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Nomenclature

Variables

θ	water temperature (°C)
u	on/off status
r	amount of imbalance electricity (kW h)
l	aggregated thermal load (kW)
α, β, γ, δ	ancillary variables in the linear counterpart

Parameters

Q	heater capacity (kW)
R	thermal resistance (°C/kW)
C	thermal capacitance (kW h/°C)
Δt	length of each time step (h)
M	mass of water in full storage (kg)
d	demand of hot water (kg)
L	heat loss (kW h)
C	specific heat capacity (kW h/kg °C)
P	rated power (kW)
η	coefficient of performance
$\mathbf{N}^+$	set of all positive natural numbers
N	number of time steps of a day
p	imbalance price ($/kW or $/kW h)
w	renewable generation (kW)
s	uncontrollable load (kW)
g	day-ahead purchased electricity (kW)
Num	total number of thermal loads
Γ	parameter indicating the tightness of thermal comfort constraints
K	value to calculate Γ
Y	general symbol that represents w or s
ε	forecast error
σ	standard deviation
X	general symbol that represents P, Q, R, C and M

Subscripts

i, t, m, n	time step index
en	environment
cur	before water consumption
low	lower limit
up	upper limit
water	water
standby	standby
0	initial state
e	energy price
c	capacity price
up	lacking electricity
down	having surplus local generation

Superscripts

^	estimation/forecast
–	average value

has become a promising candidate to provide the needed fast-response ancillary services for power systems.

The flexible loads of residential prosumers are usually aggregated to balance the variability of local renewable generation or even to provide ancillary services to bulk power systems. There are generally two categories of methods for power system operators to control aggregations of flexible loads. One is direct load control, in which the blocks of power offered by aggregators are directly dispatched by power system operators. The other one is price response, in which aggregators respond to electricity prices that reflect the relationship between supply and demand of power systems. The research of this paper lies in the latter price response field. To be specific, this paper considers an aggregator that aggregates a population of residential prosumers that owns flexible thermostatically control loads and renewable generation, and studies the optimal scheduling method used by the aggregator to arbitrage in the intraday electricity market. The proposed scheduling method maximizes the economic benefits of the whole population of prosumers in the aggregation on one hand, and naturally helps balance intra-hour differences between supply and demand on the other.

Many relevant papers have been published in this area. First of all, due to great proportion in electricity consumption and thermal energy storage capability [1,2], a series of direct load control methods have been developed to control aggregated thermostatically controlled loads for a set of purposes. For example, Lu investigated the potential of providing intra-hour load balancing services using aggregated heating, ventilating and air-conditioning loads [3]. Lu and Zhang also presented design considerations for a centralized load controller to control thermostatically controlled appliances for continuous regulation reserves [4], and further developed a novel dynamic parameter selection process to optimize the performance of it [5]. Sinitsyn et al. designed safe protocols for generating power pulses with heterogeneous populations of thermostatically controlled loads to provide ancillary services by assisting in balancing generation and load [6], and further introduced timers to endpoint load control enabling better shaping of power pulses [7]. Perfumo et al. developed a model-based feedback control strategy for load management of large groups of thermostatically controlled loads [8]. Callaway developed new methods to model and control the aggregated power demand from a population of thermostatically controlled loads to deliver load following and regulation services with application to wind energy [9]. Mathieu et al. explored state estimation and control methods to coordinate aggregations of thermostatically controlled loads to manage frequency and energy imbalances in power systems [10].

On the other hand, another group of papers have presented price-based scheduling methods for flexible resources. For example, Sossan et al. developed a model predictive control strategy for the space heating of a smart building including cogeneration of a fuel cell-electrolyzer system according to a dynamic electricity price [11]. Vasirani et al. developed an agent-based approach to model and control virtual power plants that are composed of wind power generators and electric vehicles [12]. Subramanian et al. developed and analyzed real-time scheduling algorithms for coordinated aggregation of deferrable loads and storage devices [13]. Ju et al. established a bi-level stochastic scheduling optimization model for a virtual power plant connected to a wind-photovoltaic-energy storage system considering the uncertainty and demand response [14]. Zapata et al. conducted a comparative study of imbalance reduction strategies for virtual power plants that consist of cogeneration devices and photovoltaic installations in the intraday balancing market [15].

Furthermore, some studies developed price-based scheduling or control methods for aggregated thermostatically controlled loads. For example, Lu et al. developed a state-queueing model to analyze the price response of aggregate loads consisting of thermostatically

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