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An intra-hour control strategy for aggregated electric storage space heating load

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ABSTRACT

Forecasting errors in a power system occasionally leads to situations where either production or consumption is required to be altered. In order to improve demand-side contribution under these special conditions, this paper introduces an intra-hour control strategy that allows a retailer to request regulating power from flexible loads. The load under research is electric storage space heating (ESSH) employing model predictive control (MPC) for minimizing the heating cost and ensuring customer comfort. In the proposed framework, a regulation request is sent to the loads, after which they solve the price and volume of their regulation bids and communicate the bids back to the retailer. Centrally, the retailer aims to minimize prediction error costs by finding the cheapest mix of buying regulation from the loads and settling the error later in the imbalance settlement. The proposed control strategy is tested and evaluated in dynamic simulations. The results indicate that the thermal storages can be regulated by the proposed strategy and some savings in imbalance costs are possible.

Introduction

Utilizing the flexibility available in electricity consumption is one method to improve future power systems. Consumers can be offered incentives to allow controlling of their household appliances for ancillary services [1]. Alternatively, they can be provided with electricity contracts that connect their consumption to the actual wholesale price of electricity and thus, motivates the households to alter their electricity use locally [2].

These real-time pricing (RTP) programs have proven to benefit consumers as local intelligence can automatically schedule the consumption in a cost-minimizing manner [3–7]. In order to ensure customer convenience and tackle uncertainties under RTP, model predictive control (MPC) has been considered to be an effective approach for the optimal scheduling [8–12]. For example in [8], MPC employs building thermal model and hourly spot-price information to optimize the heating sequence over a prediction horizon. The optimization is repeated during each time step by using recent measurements on system states and by executing only the first step of the optimized sequence.

Even though careful consideration has been given to the load scheduling under RTP, the local optimization may not serve the electric grid in the most desirable manner. Household loads are typically supplied by a market participant who needs to purchase the electricity hours before the actual power delivery [13]. Furthermore, the participants may be penalized if the procurement and consumption are not in equilibrium [14]. In this context, accurate forecasting is desirable but it can be challenging to achieve in the presence of demand response (DR) [15]. To tackle the prediction accuracy, [16] proposes a two-stage strategy where the day-ahead price signal is first set by using a decentralized optimization method. This sort of distributed approach enables the utilization of local information in decision making. In real-time, consumers are possibly required to pay extra according to their and the grid's actual consumption, which motivates them to be accurate in the day-ahead forecasts. Decentralized planning is also studied in [17], which uses local prediction and a distributed algorithm to define households' target load profiles. Prediction errors are dealt with by local controllers in real-time.

Another approach to reduce prediction errors is to unleash the flexibility from loads closer to the moment of electricity delivery. Ruiz et al. [18] designed a virtual power plant that aggregates domestic load flexibility and uses direct load control to adjust load in the case of power imbalance. On the other hand, price-responsive loads can be controlled by updating the price in real-time instead of using the day-ahead price signal. In [19], the authors describe a DR program where customers pay a flat rate, but can be offered coupon incentives if consumption needs to be

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Nomenclature

α	weight variable
Δc	bid price
Δu_l	bid volume
$\Delta u_{l,k}$	change in charged energy
ϵ	normally distributed random noise
$\hat{c}^{dn}$	estimated cost of down regulation
$\hat{c}^{up}$	estimated cost of up regulation
B	number of intra-hour steps
c^{dn}	cost of down regulation
c^{reg}	regulating cost for current regulation period
c^{up}	cost of up regulation
e	prediction error
k	index of time step
L	total number of bidding loads
l	index of bidding load
M	big number
N	length of prediction horizon
N^p	prediction horizon for central problem
p	electricity price
p^{dn}	price of down regulation
P^{max}	maximum load of storage population
P^{ref}	target load profile (day-ahead procurement)
p^{up}	price of up regulation
q	heat demand
R	mismatch between charging load and target load profile
r	regulating power settled as imbalance power
r^{dn}	evaluated volume of down regulation
R^{ref}	needed regulation for current regulation period
r^{up}	evaluated volume of up regulation
s	storage level in the beginning of time step
s^{max}	upper boundary of the storage level
s^{min}	lower boundary of the storage level
t	index of current time step
u	charged energy
u^*	optimal charging control sequence
$u^{d,max}$	maximum possible charged energy within time step
$u^{d,min}$	minimum possible charged energy within time step
u^{ref}	reference for charged energy
u^r	regulated charging control sequence
w	weight variable
x	binary variable indicating a given bid

reduced. Corradi et al. [20] proposed a strategy where loads are provided with a generic and real-time price signal that is based on the modeling of the price-consumption relationship. This kind of control-by-price concept is also demonstrated in [21].

In order to help retailers reduce forecasting error related costs, this paper proposes an intra-hour control strategy that allows a retailer to buy flexibility from price-responsive loads in real-time. It is assumed that the retailer purchases the hourly energy in a day-ahead spot market and that the retailer is exposed to extra costs in the case of procurement-consumption mismatch. In this framework, hourly power balance is desirable, making the intra-hour control advantageous. This study focuses on electric storage space heating (ESSH) load, i.e., domestic space heating utilizing central electric heating with a thermal storage and a heat distribution system. This heating method can provide a considerable amount of flexibility, depending on the storage size. It is also assumed that the price-flexible loads are provided with hourly spot-price defined in the day-ahead spot market and that they utilize MPC to minimize the electricity cost.

The remainder of this paper is organized as follows. The next section describes the framework of the studied system. The proposed control strategy is explained and formulated in detail in Section "Proposed control strategy". Section "Case study" provides the simulation environment and results to evaluate the proposed strategy. Finally, short a discussion on the research findings is made in Section "Discussion", followed by the conclusions in Section "Conclusion".

System description

This section introduces the system in which the proposed control strategy is applied. Assumptions on the power system markets are needed together with the description of the studied retailer and loads.

Market framework

We consider that the studied system has a day-ahead market for hourly power trading and a balancing market for real-time power trading. This corresponds to the framework currently applying in Finnish power system [22]. The major part of the energy trading occurs in the day-ahead spot market at Nord Pool, where producers and retailers make their selling and buying offers. Based on the received offers, the market clearing prices are calculated for each hour of the next day, 12–36 h before the actual delivery. In the balancing market, both production and consumption side are allowed to submit their up and down regulation bids intra-daily if they have any resources able to change the production or consumption within 15 min. The transmission system operator uses this market to buy either up or down regulation in the case of great power imbalance. The regulating prices for each hour are formed so that for the up regulation the price is equal or greater than the hourly spot price, and for the down regulation it is equal or smaller than the hourly spot price.

After the electricity delivery, all market participants are obligated to buy imbalance power to cover the mismatch between their buys or sells and the actual production or consumption [23]. The price of the imbalance power follows the hourly regulating price. For example, a retailer, whose consumption was less than the procurement, sells the extra energy at the down regulating price. On the other hand, if the consumption was greater than the procurement, the retailer is obligated to buy up regulation. Thus, the forecast errors are penalized, as the regulating prices are likely to be less profitable than the hourly spot-price.

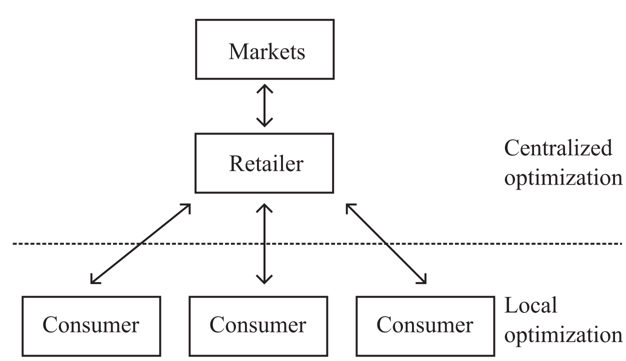

Fig. 1. Studied system. Arrows show the communication links and message directions.