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Optimizing residential heating and energy storage flexibility for frequency reserves

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ABSTRACT

The increase in intermittent renewable generation motivates participation of also the electricity consumers in maintaining the production–consumption balance of the electrical grid. This paper proposes a distributed price-based optimization scheme for involving a population of consumers in day-ahead procurement of electricity and frequency containment reserves. Energy storage charging and heating of residential houses are planned before the operating day, while taking into account uncertainties in the day-ahead electricity and reserves markets, weather conditions, and realized frequency. The proposed approach is formulated as stochastic quadratic programming problems and coordinated using a parallelized formulation of the alternating direction method of multipliers (ADMM). Chance constraints for the storage state of charge variations under uncertain reserve activation are formulated as second-order cone constraints. The numerical results illustrate the potential benefits of including consumers in the optimization of reserves.

1. Introduction

The infrastructure of the electrical grid should be updated, due to the coming challenges with changes in production and consumption of electricity. The increasing contribution of intermittent renewable generation and new sources of consumption, such as electric vehicles, complicate sustaining the real-time equilibrium between the production and consumption [1]. Incorporating the consumption in maintaining the production-consumption balance is a major part in the envisioned smart grid [2]. This demand response can be especially effective when coupled with potential energy storage capabilities [3]. Actually controlling the demand can be achieved by issuing price-based incentives to the energy consumers or by assuming more direct control over the loads [2]. However, a combination of these approaches might be necessary in order to achieve optimal benefits, at different time-scales [4].

This paper aims to construct a framework for an aggregating electricity retailer for participating in electricity markets with the responsive electric heating demand of its aggregated residential households. The consumers are incentivized with dynamic electricity prices for planning their consumption schedules, as well as a possibility to participate in reserve operation and income by providing promises of specific amounts of potential demand flexibility. The intra-hour reserve participation is then realized by providing required changes to the consumption levels in proportion to their promised flexibilities. The proposed distributed price-based optimization framework takes into account uncertainties in the utilized markets, as well as in the amount of electricity consumed by the houses and in the activated reserves.

2. Related research

There has been a sizeable amount of research dedicated to scheduling groups of various electrical loads under uncertainties. Uncertainties resulting from day-ahead planning can be considered using scenario-based approaches such as stochastic programming [5], robust formulations [6], or with hierarchical solutions [7]. In addition, multiple different objectives can be considered simultaneously with multiobjective optimization approaches [8]. For obtaining a tractable version of the uncertainty-infused problem, a scenario-based approach is frequently utilized where multiple scenarios are considered simultaneously within an optimization problem [9,5,10], which can be useful when decisions have to made in multiple stages. Robust formulations are especially useful for minimizing the risks ensuing from the uncertainties [6]. Hierarchical solutions can be employed to cater to more holistic grid management [11] or e.g. for combining multiple control methods [7]. Furthermore, in contrast to more traditional optimization methods, approximate approaches using heuristics and e.g. artificial neural networks have also been applied in the energy domain [12]. Additionally, metaheuristics can be used to further *“orchestrate an interaction between local improvement procedures and higher level strategies to create a process capable of escaping from local optima and performing a*

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Nomenclature

$\overline{C}_{n,t}^{\omega_1,\omega_2}$	expected energy storage state of charge of consumer n (kWh)
λ^k	Lagrange multipliers for coordinating distributed optimizations, iteration k
x_n^k	consumer n decision variables, iteration k
δE_t	bid to reserve market (kW)
$\delta P_{\downarrow,n,t}^{\omega_1}$	decreasing reserve commitment of consumer n (kW)
$\delta P_{\uparrow,n,t}^{\omega_1}$	increasing reserve commitment of consumer n (kW)
Δt	time step (1 h)
γ	damping parameter
$\mathbb{X}_n$	consumer n constraint set
Ω	amount of discrete scenarios
ω_1	scenario superscript of day-ahead market and reserve prices
ω_2	scenario superscript realized consumption and reserve utilization
σ_f^2	variance of grid frequency deviation ($1/s^2$)
A_n	consumer n linear inequality constraint matrix
$C_{max,n}$	energy storage capacity (kWh)
E_t	bid to electricity market (kW)
$f_t^{\omega_1,\omega_2}$	realized grid frequency for the certain hour (1/s)
$G_n(\cdot)$	cost function augmented with constraints
$g_n(\cdot)$	consumer n cost function
H	optimization horizon
$K_{r,t}^{\omega_1}$	price of frequency reserves (EUR/kWh)
$K_{s,t}^{\omega_1}$	price of electricity (EUR/kWh)
$M_{repl,n}$	replacement cost of energy storage (€/kWh)
N	amount of consumers
$P_{max,n}$	maximum charging power (kW)
$P_{n,t}^{\omega_1}$	scheduled energy storage charging of consumer n (kW)
$Q_{n,t}^{\omega_1}$	heating energy demand predictions (kW)
t	subscript denoting current hour
$T_{e,n,t}^{\omega_1,\omega_2}$	realized external temperatures (°C)
$T_{e,n,t}^{\omega_1}$	external temperature predictions (°C)

robust search of a solution space." [13] However, in the following, scenario-based approach is utilized to account for the uncertainties in costs and demand and additionally robustness is considered in the consumers' local constraints.

For example, Pantoŝ [10] utilized scenario-based approaches in scheduling electric vehicle storages for maximizing renewable energy utilization. However, reserve market participation was not considered. Similarly, Nguyen et al. [9] utilize the thermal dynamics of houses in scheduling and bidding on day-ahead markets, but did not consider reserves participation. Furthermore, Momber et al. employed a Monte-Carlo stochastic programming approach but also included risk aversion [14]. In contrast, reserve market participation was considered by Warrington et al. [15] for rolling dispatch of loads. Reserve markets were also considered by Donadee and Milić [16], but hourly optimization was again considered in contrast to day-ahead markets.

However, the consumers can cooperate for example by agreeing to provide varying amounts of reserves under different situations, which can result in savings and better performance of the overall system. Many proposed game-theoretic approaches where the participation prices between the consumers are openly resolved, have been limited in some aspects. For example, Zugno et al. [5] consider a stochastic bi-level electricity pricing optimization, but do not consider reserves and obtain the solution using centralized methods. Similarly, a model for optimizing the retail price of electricity was proposed by Meng and Zeng [17], however, without accounting for uncertainties or reserve participation. In addition, many authors [18,19] have chosen to consider only utility functions for modelling the electricity consumption, in addition to dismissing stochastics as well as reserve markets.

A popular approach for coordinating price-based optimization is the alternating direction method of multipliers (ADMM) [20], which has recently been widely utilized in research involving the scheduling of various loads. For example, ADMM has been used in solving the optimal power flow problem regarding network constraints [21], and unit commitment [22]. In addition, ADMM has been utilized for sizing of distributed energy storage systems [23]. Electric vehicles have been especially considered for coordinating demand response for facilitating e.g. valley-filling, cost minimization, and network and charging station capacity compliance [24,25]. However, the proposed approaches have not considered the potential of reserve market participation. Dispatching the frequency reserves using local measurements has however been proposed for example by Brooks et al. [26] for generic responsive loads, and Nazari et al. [27] for further coordinating their effects to avoid inter-area oscillations. However, day-ahead participation of residential heating demand in reserves markets with uncertainties taken into account has not been sufficiently considered in any previous publication, to the best of our knowledge.

In the proposed method, stochastic programming is utilized, with sample average approximation for evaluating the expected costs. More specifically, the contribution of this paper consists of

- Development of a novel method for facilitating the participation of multiple residential houses for the reserve market where:
  - The houses can independently optimize in a distributed fashion with respect to price-based incentives and retain some level of privacy.
  - Uncertainties in prices and energy demand are taken into account before the operating day with stochastic programming but different levels of participation of the consumers are enabled with inter-scenario coordination.
  - Level of comfort constraints are taken into account robustly from uncertain amount of reserve demand with chance constraints.
- Various simulations with different levels of optimization are run to evaluate the potential monetary benefits of reserve participation.

Optimization methods are developed for planning the schedules of the heating and energy storage charging of the houses in question, before the actual prices of the electricity markets are known. A stochastic programming model is developed, and a distributed version of the alternating direction method of multipliers is utilized for coordinating the distributed optimization in order to satisfy global constraints. In addition, different levels of optimization are simulated in order to illustrate how taking into account the acquisition costs and reserve prices as well as their uncertainties could potentially reduce the associated costs.

3. Optimization model formulation

This section describes the developed framework which aims to minimize the cost of acquiring electricity from the day-ahead market, while maximizing revenue from participation in a reserves market. At first, the main assumptions of the models are described. Next, the consumer optimization problem is detailed. Then, the aggregate constraints are formulated and a method for coordination between the consumer problems is proposed, for the two stages of day-ahead planning pertaining to the periods before and after the realization of the actual prices.

3.1. Problem assumptions

The aggregator has to bid on the day-ahead markets for electricity