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A market-oriented hierarchical framework for residential demand response

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ABSTRACT

The integration of a great deal of uncertain renewable sources in future grids will require more operational flexibility. Demand response (DR) can provide the load shaping potentials thereby assuaging the need for operational flexibility. To this end, this paper intends to develop a framework focusing on realization of domestic storage space heating DR capability in balancing market. The developed framework consists of two hierarchical stages named energy market stage and balancing power market stage. The first stage deals with customers' day-ahead decisions in energy market. In this stage, the system operator releases day-ahead energy prices in response to which customers optimize their electricity usage to minimize their energy expenses. The second stage optimizes customers' intra hour load scheduling decisions in balancing power market. In the second stage, up/down power regulation incentives are offered to customers who, in the hope of achieving monetary gains, modify their promised day-ahead decisions. Performance of the framework is verified through simulations on Finnish case studies. According to the obtained results, the framework allows the customers to make savings in energy expenses as well as the system operator to benefit from DR.

Introduction

The inspiration of smart grid is the integration of renewable generation, distributed energy resources and augmenting the energy efficiency in power and energy systems. Due to the high penetration of intermittent renewable generation and the deregulation of power market there will be a considerable need for additional flexibility for a reliable power system operations [1]. This flexibility can be readily deployed by activating residential demand response to induce noteworthy technical, economic and ecological benefits [2]. Residential demand response needs to be activated in the balancing power market for increasing the up/down ramping flexibility. Implementing price based demand response can create an interactive scheme which can not only reduce the energy payment but also mitigate the mismatch between demand and supply and increase the monetary gains.

In a typical household in Finland, thermostatic loads such as heating, ventilation and air-conditioning (HVAC), and electric water heaters (EWH) accounts for about 70% of the total household energy consumption [3]. There are analyses that showed that HVAC loads give a very good result in terms of ramping up and down response without deteriorating customer's thermal comfort and can prove to be a good candidate for providing fast demand response [4,5].

The research on HVAC loads management for customers' economic benefit and systems operation perspective have received a lot of attention in the literature. The following works [6–10] presented frameworks for activating the demand response in energy market only. The work [6,7] used a linear programming approach for storage control under dynamic power pricing to reduce the customer energy payment. The work in [8] presented a demand response model for coordinating the operation of partial thermal storage and thermal masses of building structure to reduce customer's energy payment in day-ahead energy market only. The authors in [9] developed a framework for optimal scheduling of the EWH based on price and consumption forecasts without violating the consumers' thermal comfort. The research in [10] coordinated the load management of HVAC and EV to bring customer economic savings in energy market.

Nevertheless, there are papers whose focuses were assessing the DR potential of domestic heating load i.e. HVAC and EWH in balancing power market. For instance, the study in [11] explored the system-wide power balancing potential through EWH load considering customers thermal comfort. The results reported are

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Nomenclature

ΔP_h^s	deviation from original charging schedule (kW)
C_h^e	hourly electricity price (€/kW h)
E^s	maximum storage capacity (kW h)
P_h^s	storage charging power (kW)
Q_h^s	discharged energy from storage during hour h (kW h)
S_0^E	initial level of thermal storage (kW h)
S_h^E	stored energy during hour h (kW h)
S_h^l	stored energy lost during hour h (kW h)
Z^{DA}	day-ahead cost (€)
b_h^e	bonus price during hour h (€/kW h)
r_h	auxiliary variable
h	index of hours (hours)
P^{ch}	charging power (kW h/h)
$q_{h'}$	average heat demand (kW h) during hour h and
SoC	state of charge of thermal storage (p.u.)
γ	coefficient of thermal storage loss
λ	binary variable for (1) up and (−1) down regulation
μ, σ	weighting coefficients for reserving flexibility
Δh	time step used in the simulation
β, τ_h	dual variables of the model
π	weighting coefficient between expected demand and stored heat energy

Acronym

DR	demand response
EV	electric vehicle
EWH	electric water heater
HVAC	heating ventilation and air-conditioning
LP	linear programming
TSO	transmission system operator

valuable however the control scheme for regulating the load is non-optimal hence a large number of EWH are required to perform the same regulation services. To address that shortcoming, the work [12] quantified the HVAC load potential for providing intra-hour power balancing services in balancing power market. The research reported the significant capability of HVAC load for power balancing reserve. The potential of managing thermostatic load for different ancillary services in balancing power market were also studied in [13,14]. The papers demonstrated that the thermostatic load aggregation in balancing power market can be beneficial for both the customers and system perspective. A novel temperature set point control algorithm for EWH control for mitigating the power system disturbances was developed by [15]. The research demonstrated that enrolling the residential load in the balancing market for power regulation can be a key enabler to increase the utilization of intermittent generation in energy mix. The paper [16] demonstrated the feasibility of unleashing up/down regulation services from commercial HVAC loads. The work in [17] designed a centralized control module for providing continuous up/down regulation services in balancing market.

Most of the above reviewed papers quantified the potential benefits of HVAC and EWH loads in balancing market and did not thoroughly discuss about the rational realization and activation of this DR potential in balancing market. Moreover, most of the works neglected to consider how a residential consumer can jointly participate in energy and balancing power market by co-optimizing the energy attainment and reserving some up/down flexibility in balancing market with regarding their preferences and thermal comfort. Although, this problem is addressed in [5,18], a comprehensive model is required to realize the total potential of demand response considering customer preferences.

In Nordic power market system, the aggregator is obliged to announce their day-ahead power proposal to the corresponding subsequent transmission system operator (TSO) before the actual power delivery phase. However, the aggregator can suffer from forecasting errors and may face power mismatch issues during the actual delivery phase which consequently result in large penalties for violating the hourly power nominations. To cope with the power mismatch penalty, the aggregator can control the group of storage space heating load in balancing market to minimize the power balancing penalty instead of buying the balancing power from TSO. Under this background, this paper offers a hierarchical framework for engaging the residential customers to participate in balancing power market. The decision support tool comprises of two-stages. In the first stage of DR management, named as energy market stage, customers are given day-ahead hourly prices to optimize their load usage in order to achieve minimum energy payment. During this stage the customer's energy management decisions are determined. In order to enroll customers in balancing power market, the second stage is setup which provides hourly monetary incentive to customer to encourage for the load shaping by up/down regulating[1] the load. The customers respond to the load regulation request if they get a good incentive to modify their earlier made load commitment.

The rest of the paper is organized as follows. The following section describes the system modeling. The proposed two-stage demand response framework is formulated in Section 'Proposed two-stage framework for activating residential HVAC demand response'. Section 'Case study' critically evaluates the performance the proposed framework through case studies. The discussion part is penned in Section 'Discussion'. While Section 'Conclusion' outlines the main conclusion of our work.

System model

This paper considers an efficient interaction of a residential customer with an electrical aggregator under the smart grid paradigm. The structure of the considered smart environment is shown in Fig. 1. The electric aggregator is an agent which acts on behalf of a group of customers for purchasing electricity and provide means for activating the demand response. In this paper, it is considered that electric aggregator provides a service to help the consumer in day-ahead scheduling and, if necessary, to muster the possible load flexibility from a group of several users into a flexibility product which can be sold on the balancing market. The customer is equipped with storage space heating system with flexible charging capability. Equipped with the necessary communication infrastructure and smart meter, the aggregator can communicate with the customer in real time. A home load energy management system is responsible for flexible load scheduling at the customer end. The energy management system can communicate with storage heating unit via an inexpensive RS 485 link.

[1] Here, up/down regulation refers to the decrease/increase in hourly consumption.