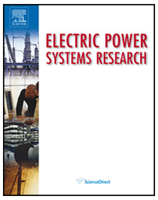
Electric Power Systems Research 145 (2017) 44–54

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



A control framework for the utilization of heating load flexibility in a day-ahead market

Antti Alahäivälä [a,*], James Corbishley [b], Jussi Ekström [a], Juha Jokisalo [c], Matti Lehtonen [a]

[a] Department of Electrical Engineering and Automation, Aalto University, Espoo FI-00076 AALTO, Finland
[b] Department of Economics, Aalto University, Helsinki FI-00076 AALTO, Finland
[c] Department of Energy Technology, Aalto University, Espoo FI-00076 AALTO, Finland

ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form
15 December 2016
Accepted 17 December 2016

Keywords:
Demand response
Direct electric space heating
Aggregator
Nord Pool

ABSTRACT

A flexible demand-side can have a positive influence on electricity markets and the entire electricity infrastructure once the flexibility is properly harnessed. Such a goal is becoming attainable with emerging smart grid technologies which allow the controlling of consumption and its aggregation to electricity markets. In this paper, we focus on the aggregation of detached houses with direct electric space heating (DESH) in terms of two main targets. Firstly, a basic framework for the aggregation is proposed and secondly, the benefit of the heating load flexibility for the aggregator and the consumers is investigated in the Nordic day-ahead electricity market Elspot. The loads are controlled with a simple strategy based on a centrally transmitted thermostat set-point signal, and this strategy is benchmarked against a more complex direct load control approach. As there is great flexibility potential in the heating load, the aggregattor is assumed to act as a price-maker in the market, where it seeks to minimize its energy cost and schedule the flexibility. The loads participating in the control are provided with a bonus based either on the caused inconvenience or the provided flexibility. In simulations studies, we use a detailed Finnish detached house population model and hourly market data from Nord Pool's Elspot.

1. Introduction

Demand response (DR) enables an improvement in power system flexibility. With properly implemented system integration, the electricity demand can be altered in such a way that it is able to participate in the maintenance of power balance in different time scales [1]. In addition to increasing the grid flexibility, DR improves the efficiency of electricity markets if the market demand becomes more price elastic [2].

The source for this flexibility lies in the ability to shift or momentarily change the consumption of certain load types, such as electric heating load in detached houses [3]. In Finland, the heating energy consumed by residential buildings in 2012 was approximately 59 TWh, of which the portion of electric heating of detached houses was 10 TWh [4]. This covered nearly 12% of the Finnish electricity consumption [5]. As shown in [3] and [6], the space heating of a typical Finnish detached house provides flexibility, owing to the thermal inertia of the building and the allowed variations in the indoor temperature. Thus, motivated by the considerable amount of heating energy consumption in Finland and the possibility to momentarily alter it, this study investigates the DESH of detached houses.

In a deregulated market environment, one possible market place for electric heating load flexibility is a day-ahead electricity market. Residential consumers are unable to participate in the market directly due to their relatively small consumption, which is why a retailer is required to enter the market on their behalf. This retailer, called an aggregator in this study, can financially benefit from the DR [7]. However, a strategy to coordinate the consumption is required. The strategy needs to consider how to motivate the consumers to share their flexibility, how to exploit the flexibility in the market, and how to control the consumption. Literature provides several studies where either one or more of these aspects are considered.

The strategies, or DR programs, for consumers to participate in are typically divided into real-time pricing (RTP) or incentive based options [8]. In the case of RTP, the consumers receive a time-varying tariff rate and thus have the motivation to alter their consumption. The received rate can be the electricity market price, which consumers exploit locally and minimize their electricity cost as in [9].

---

* Corresponding author.
E-mail addresses: antti.alahaivala@aalto.fi (A. Alahäivälä), james.corbishley@aalto.fi (J. Corbishley), jussi.ekstrom@aalto.fi (J. Ekström), juha.jokisalo@aalto.fi (J. Jokisalo), matti.lehtonen@aalto.fi (M. Lehtonen).

http://dx.doi.org/10.1016/j.epsr.2016.12.019
0378-7796/© 2016 Elsevier B.V. All rights reserved.

Nomenclature

Indices

g	climatic zone index
i	bid index
j	coefficient index for the regression model
k	time step index
l	averaging block index
m	building index

Parameters

β	constant term of the regression model
β^{P}	coefficient for aggregated heating power
β^{u}	coefficient for control signal
$\boldsymbol{\beta}^{\mathrm{c}}$	coefficient for outdoor temperature and heat gains
$\mathbf{c}$	values for outdoor temperature and heat gains
ΔP	change in aggregated heating power
ΔT	temperature band for central control
Δt	discretization time step
ϵ	error term of the regression model
λ	bid price
$\bar{P}$	upper boundary of aggregated heating power
$\bar{p}$	rated heating power of a building
$\bar{u}$	upper boundary of control signal
π	spot-price without optimized heating load
π^*	spot-price with optimized heating load
$\underline{u}$	lower boundary of control signal
$A1 - A4$	building thermal model parameters
$B1 - B3$	building thermal model parameters
B^{C}	convenience based bonus
B^{F}	flexibility based bonus
b^{P}	estimated value for the regression model coefficient β^{P}
b^{u}	estimated value for the regression model coefficient β^{u}
c	parameter for outdoor temperature and heat gain influence
F	scaling factor
G	number of climatic zones
I	number of bids in residual supply curve
K	length of optimization period
$K^{\uparrow\downarrow}$	number of hours control used
K^{b}	length of averaging block
L	fixed electricity demand
M	number of optimized buildings
M^{real}	scaling factor
n^{c}	number of coefficients for outdoor temperature and heat gains
n^{P}	number of coefficients for aggregated heating power
n^{u}	number of coefficients for control signal
$p^{\downarrow}$	decrease in heating power due to control
$p^{\uparrow}$	increase in heating power due to control
P^{uc}	uncontrolled aggregated heating power
p^{uc}	uncontrolled heating power of a building
Q	sum of bid quantities
q	bid quantity
R	large number
S	estimated daily savings
T^{set}	base value of thermostat set-point

Variables

δ	quantity activated from a bid
P	aggregated heating power
p	heating power of a building
P^{g}	the aggregated heating power of a climatic zone
s	slack variable
T^{a}	indoor temperature
T^{s}	building mass temperature
u	generic control signal
v	indicates bid activation (binary variable)
x	auxiliary binary variable

Alternatively, the rate can be tailored to cause the desired aggregated response in the consumption. In [10] and [11], a controlling entity utilizes an aggregated load model to predict the response and solves the electricity price of consumers in order to achieve its own goals. The RTP programs provide the consumers with the freedom to react to the control signal but at the same time exposes them to uncertain tariff rate.

Instead of a time-varying rate, a common approach to motivate the consumers' participation in DR programs is to provide them with monetary incentives. The incentives are typically used with centralized control approaches [8]. The centralized approach refers here to control strategy where a communicated control signal aims to change the consumption directly as for example in [12]. In [13], the centralized approach is employed in a control framework minimizing the energy cost in a wholesale electricity market. The approach first optimizes the desired load profile and then solves the control signal communicated to the loads. The authors in [14] integrate a building thermal model in an aggregator's bidding problem and use the heating load flexibility in the profit maximization of the aggregator. They assume that the aggregator is able to control the loads. Some studies also focus on defining the amount of incentive paid to the consumers. In [15], the aggregator has a set of predefined DR contracts (price, quantity, and duration of DR) with flexible consumers that it then utilizes in its profit maximization self-scheduling in a day-ahead market. The authors in [16] include the incentive-based DR in the optimization problem of a retailer in a day-ahead market. The optimization uses the price elasticity of the consumers to model their response to the incentives. A somewhat similar approach is also investigated in [17], where monetary incentives (coupons) are sent to consumers if the load needs to be reduced in a real-time market. To cope with the uncertain response of the consumers, the coupon prices are solved iteratively, i.e., the loads are asked for their response to the coupon which is then updated accordingly.

In our approach, the aggregator is able to directly control the loads. Contrary to the aforementioned studies, the aggregator shares the estimated benefits of the flexibility with the consumers via bonuses solved after the actual electricity delivery. As suggested in [18], consumers may actually value centralized direct load control strategies with flat and discounted tariffs more than strategies with time-varying prices, as long as the control is tightly bounded and can be overridden locally. These observations also inspire our control framework, which employs centrally broadcasted control signals, a flat tariff with bonuses, and which preserves the consumers' ability to affect the control locally. The proposed control framework is also inspired by the work done in [10,11], which use RTP, central optimization, and simple and local decision of heating load to obtain aggregated response. However, the tariff rate is constant in our framework because the consumers may not be willing to receive time-varying prices.

Existing literature also covers studies which aim to assess the monetary benefits of DR or its market impacts. The procurement cost of a retailer with flexible consumption were minimized in the German case study in [7]. The authors in [13] investigated the