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Residential heat pump as flexible load for direct control service with parametrized duration and rebound effect

Emeline Georges [a,*], Bertrand Cornélusse [b], Damien Ernst [b], Vincent Lemort [a], Sébastien Mathieu [b]

[a] Energy Systems Research Unit, Thermodynamics Laboratory, University of Liège, Liège, Belgium
[b] Systems and Modeling Research Unit, Department of Electrical Engineering and Computer Science, University of Liège, Liège, Belgium

HIGHLIGHTS

- A direct control flexibility service of residential heat pumps by a load aggregator is proposed.
- The service consists in upward and downward power modulations with a constrained rebound effect.
- Results show a larger potential for upward modulations than for downward modulations.
- The constrained rebound effect significantly impacts the achievable modulation amplitude.

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ABSTRACT

This paper addresses the problem of an aggregator controlling residential heat pumps to offer a direct control flexibility service. The service consists of a power modulation, upward or downward, that is activated at a given time period over a fixed number of periods. The service modulation is relative to an optimized baseline that minimizes the energy costs. The load modulation is directly followed by a constrained rebound effect, consisting of a delay time with no deviations from the baseline consumption and a payback time to return to the baseline state. The potential amount of modulation and the constrained rebound effect are computed by solving mixed integer linear problems. Within these problems, the thermal behavior of the building is modeled by an equivalent thermal network made of resistances and lumped capacitances. Simulations are performed for different sets of buildings typical of the Belgian residential building stock and are presented in terms of achievable modulation amplitude, deviations from the baseline and associated costs. A cluster of one hundred ideal buildings, corresponding to retrofitted freestanding houses, is then chosen to investigate the influence of each parameter defined within the service. Results show that with a set of one hundred heat pumps, a load aggregator could expect to harvest mean modulation amplitudes of up to 138 kW for an upward modulation and up to 51 kW for a downward modulation. The obtained values strongly depend on the proposed flexibility service. For example, they can decrease down to 2.6 kW and 0.4 kW, respectively, if no rebound effect is allowed.

1. Introduction

The increase in decentralized power generation and the integration of intermittent renewable energy sources in electrical distribution systems have entailed a rising interest in the use of load modulation services [1]. These services are provided by load aggregators which manage and trade the demand flexibility of electricity consumers. Among flexible loads, thermostatically controlled loads (TCLs) have been shown to present suitable characteristics for active demand response through the manipulation of temperature set points [2,3]. Different signals are used to trigger load modulation: forward price signals [4,5], power flow and voltage level in a distribution line [6] and residual load [7]. Two mainstream approaches are distinguished. The first one takes the point of view of the end-user and aims at maximizing its financial benefit [8,4,9,10]. The second approach is based on a centralized method to meet system-level needs, such as load following [11,12], minimum electricity generation costs or CO_2 emissions [13]. To this end, end-users are pooled to provide an aggregated flexible load [14,15].

This study takes the point of view of a load aggregator controlling a cluster of domestic heat pumps. The aggregator wants to offer direct control flexibility services. The services consist of an

* Corresponding author.
E-mail address: emeline.georges@ulg.ac.be (E. Georges).

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Nomenclature[1]

Parameters

H	number of periods in the horizon
$\mathcal{H}$	optimization horizon $\{1,\ldots,H\}$
n	number of modulation periods
l	number of delay periods before payback
k	number of payback periods
$\mathcal{K}(\tau,(n-1)+l+k)$	flexibility service horizon $\{\tau,\tau+1,\ldots,\tau+(n-1)+l+k\}$
$\mathbf{A}^i$, $\mathbf{B}^i$, $\mathbf{E}^i$	parameters of state-space model
C	thermal capacitance
c_i, d_i, f_i	parameters of the heat pump model
dt	period duration
COP_t	heat pump coefficient of performance
ε	penalty for the payback imbalance
Γ_t	exogenous power consumed
Q_t^g, Q_t^{sol}	internal heat gains, solar gains
π_t^+	buying price of electricity
π_t^-	selling price of electricity
R	thermal resistance
σ	state deviation tolerance from baseline
λ	state constraint relaxation
T_t^a	ambient temperature
T_t^{su}	water supply temperature
$\mathbf{u}_t$	state-space model parameters
$\mathbf{x}^i$	initial state

Variables

δ_t	modulation amplitude
δ_τ^*	minimum modulation amplitude over n periods
I^+	maximum positive deviation after a modulation
I^-	maximum negative deviation after a modulation
P_t	total consumption
P_t^+	power bought from the grid
P_t^-	power sold to the grid
Q_t	heat pump thermal capacity
T_t	temperature
W_t	compressor electrical power consumption
$\mathbf{x}_t$	state variable
y_t	heating mode

Superscripts

g	gain
sol	solar
n	nominal
a	ambient
w	water
su	supply
s	space heating
i	indoor
m	massive
l	light
int	internal

upward or downward modulation for a fixed number of periods followed by a constrained number of periods characterizing the rebound effect. The achievable power modulation amplitude is determined with respect to a reference baseline. This baseline is such that it minimizes the energy costs for the end-user. The activation of the flexibility is performed in three steps: (i) the modulation, (ii) a delay period with no deviations from the baseline consumption, and (iii) a payback period during which deviations in consumption occur to allow the heat pumps to return to their baselines. The amplitudes of the achievable modulations and of the deviations during the payback are well defined within the service.

The interest in quantifying the flexibility of heat pumps within a well-defined flexibility service resides in the opportunity to exchange it as a commodity in the electrical system and electricity markets. Different actors could resort to this flexibility service: an electricity retailer could use it either to balance its portfolio as a balance-responsible party or to adjust its consumption according to day-ahead spot market prices. In the electricity market, deviations from the positions stated to the system operator, in this case, the baselines, expose the market participant to a penalty based on the imbalance tariff. Therefore, the knowledge of the payback following the modulation is key information to activate the flexibility service. A system operator could rely on the service to relieve a congestion in a line or a transformer. The quantification of the payback resulting from the modulation allows the system operator to activate the service without creating congestions further in time. Finally, a system operator could also rely on this service for balancing purposes [16,17]. Here again, the knowledge of the payback avoids the system operator reaching an unpredicted system imbalance following the activation of the modulation.

The following studies focus on detailed demand-side models with TCLs. Pavlak et al. [18] investigate the potential of using the thermal mass of office buildings to minimize peak demand. A day-ahead multi-objective optimization is implemented to provide the modulation service at minimum cost for the end-user and minimum frequency regulation cost. The optimization also determines the optimal time period to activate the load modulation. The study is extended to a portfolio of office buildings in [19] and the possible additional benefits retrieved from synergies between the buildings are outlined. De Coninck and Helsen [20] propose a bottom-up approach to determine the flexibility of buildings and heating, cooling and air-conditioning systems. Three optimal control problems are solved to determine, first, a cost-optimal baseline for the consumer, and then, the maximum upward and downward modulations available during a given time span of the day. Ali et al. [21] propose a similar optimization scheme to [20] that is applied to residential demand response. The cost-optimal day-ahead prediction of the baseline is followed by an intra-day modulation with the introduction of "bonus" price incentives. A sensitivity study of the percentage of storage capacity allocated to the day-ahead and to the intra-day optimizations is carried out. The study also proposes a method to aggregate cost functions to optimize a cluster of systems and to model the price elasticity of such loads for unit commitment applications.

In light of the literature review, the first contribution of this paper lies in the investigation of a flexibility service with detailed models of thermostatically controlled loads. The second contribution is the characterization of the payback following the activation of the upward and downward power modulation service and of its influence on the achievable modulation amplitude for different periods of the day. The characterization of the payback is particularly useful for operational planning of the distribution network and real-time activation of the service by different actors. The methodology is therefore complementary to the methods presented in [20,21] by constraining the payback time and character-

[1] Powers are taken as positive when consumed and negative when produced. A positive modulation corresponds to an increase in consumption. Variables obtained for the baseline are denoted with a $\dot{\bullet}$.