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Demand response potential of model predictive control of space heating based on price and carbon dioxide intensity signals

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ABSTRACT

This paper reports on a simulation-based study that investigated the demand response potential of a model predictive controller (MPC) for space heating defined to minimize a weighted sum of electricity costs and CO_2 emissions. The performance of the MPC was compared to a traditional controller and the results showed that an MPC with no weight on CO_2 emissions reduced the total electricity costs, shifted consumption from high to low load periods and reduced consumption in the hour with the yearly maximum grid load; but it could also cause an increase in CO_2 emissions. Contrary, the MPC with no weight on electricity costs reduced CO_2 emissions; but it only reduced total costs marginally, it could cause a shift of consumption from low to high load periods and it increased consumption in the hour with the yearly maximum grid load. Finally, if the MPC used a weighted sum of electricity costs and CO_2 emissions a range of intermediate results were obtained. The weighting factor can thus be used either to balance the performance of the MPC with respect to all performance indicators or to maximise it with respect to one indicator of particular interest.

1. Introduction

A characterizing feature of the electricity grid is that there always has to be an instantaneous balance between demand and supply. This is currently ensured by adjusting electricity production and network facilities to meet demands. However, sheer supply-side management of the balance becomes an increasing challenge as more renewable energy sources (RES) are introduced into the system because the production from the RES is intermittent and uncontrollable by nature. There is, therefore, a growing interest in exploring the potential of Demand Responses (DR) [1–7]. DR refers to actions on the demand side in response to certain conditions in the electric grid [7] and can be used to serve a variety of purposes. DR can lower peak demands and hence reduce the need for expensive peak load capacity and network facilities or it can serve as a means to flatten the demand profile to obtain efficient operational conditions for the generators [3,4,6,7]. DR can also be used to shift demands from one period to another, i.e. to achieve cost savings or to increase the utilization of supply from RES.

Households account for 26% of the total gross energy consumption in the European Union [8] whereof 50% is used to operate heating, ventilation and air conditioning (HVAC) systems for space conditioning [9]. Energy consumption for household HVAC thus constitutes a large DR potential if it can be made flexible e.g. through the concept of model predictive control (MPC) [10–15]. Nevertheless, household electricity loads are seldom used for DR, mainly because the DR potential is distributed over a large number of small loads. This requires investment in a large number of meters, communication and control devices, and a management system that coordinates and aggregates the small individual loads into a DR resource of significant size to electric system planners and operators (PO). However, this is likely to change as equipment costs decrease and the PO introduce demand response programs that facilitates participation of small household loads [5].

1.1. Demand response programs

DR can be established through different types of DR programs and are often divided into direct and indirect control programs [1,4,5]. In direct control programs the consumer give the PO direct control of electrical loads while in indirect control programs the consumer retains full control of the electrical loads and the PO can only try to change the consumption pattern indirectly. An example of indirect control is price-based DR programs where the flexibility demand from the PO is reflected in a data signal containing future time-varying electricity prices. This is an attempt to motivate con-

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sumers to perform DR by enabling them to save money by reducing consumption in high price periods or by shifting consumption from high to low price periods.

It is common to subdivide price-based DR programs according to their pricing structure which is either static, dynamic or a mixture of both. One example of a static pricing structure is Time-Of-Use (TOU) tariffs which divide a day or a week into periods with different average electricity prices [1,2,16]. The objective of such programs is to flatten out consumption and reduce peaks [1]. DR programs based on TOU tariffs are relatively simple as there is no need for an ongoing communication of a price signal to the consumers. However, TOU tariffs are not guaranteed to always have an appropriate effect on consumption because an average electricity price does not reflect the actual state and needs of the electric system in periods that diverge significantly from the average. Dynamic pricing, on the other hand, has no pre-fixed price for specific time blocks. Instead they vary dynamically over short time periods, e.g. minutes or hours, and can, therefore, better indicate the actual state of the grid. An example of a dynamic pricing structure is day-ahead Real-Time Prices (RTP) where the wholesale prices are announced one day ahead in time [1]. Price-based DR programs can also be a combination of static and dynamic price structures and one example of this is Critical Peak Pricing (CPP) which is based on static TOU tariffs but dynamically adds an additional peak price during critical events or very high wholesale prices [1,17].

A limitation of a dynamic price signal based solely on the spot market price is that it does not necessarily reflect the environmental impact of the power production in a given time block [18]. An additional data signal containing the future time-varying CO_2 intensity of the available electricity could be used as a supplement to the price signal to take environmental impact into account.

1.2. Related work and aim of this paper

Several studies make use of price-based DR in relation to space conditioning, e.g. [12–15], but there are, to the knowledge of the authors, no reported studies involving a combination of price and CO_2 signals. The few studies found that investigate the use and potential of applying a combination of price and CO_2 signals in indirect DR programs are related to electricity consumption in household appliances. Tsagarakis et al. [19] solve a bi-objective optimization problem where the objectives are to minimize daily electricity costs and CO_2 emissions associated with residential wet load appliances (dishwasher, washing machine and dryer). They use day-ahead RTP data from the United Kingdom and find that there is a trade-off between costs and CO_2-emissions: When a relatively high weight is assigned to one of the objectives, it will reduce the saving on the other. A similar study by Paridari et al. [20] applies mixed integer linear programming to optimize the daily scheduling of wet loads and charging/discharging of a battery. Their objectives are to minimize electricity costs and CO_2 emissions using Swedish data for CO_2 intensity and RTP from Nordpool [21]. They also find a trade-off effect between electricity costs and CO_2 emissions, but one that is more significant than in Tsagarakis et al. [19] as their optimized controller will perform worse on one of the objectives compared to a non-optimized baseline when a sufficiently large weight is put on the other. This means that a controller that seeks solely to minimize costs can lead to a performance that increase the total CO_2 emissions compared to a traditional control strategy.

However, the indicated existence of a trade-off effect between electricity costs and CO_2 emissions in DR programs for electricity consumption in household appliances cannot immediately be transferred to control of space heating. The reason is that scheduling of appliances is optimized using a prediction horizon of a single day whereas MPC of space heating probably needs a longer prediction horizon due to the time constant of the thermal capacity of the building constructions. The aim of this paper is, therefore, to report on a simulation-based study that investigated the performance of an MPC for space heating when applying a combination of RTP and CO_2 signals. Various performance indicators were used. It was investigated whether there was any trade-off effect between electricity costs and CO_2 emissions using the MPC with different prediction horizons compared to more traditional controllers. The RTP and CO_2 signals used in the study were from the Danish electricity grid which has a large share of wind power. It was therefore also investigated whether an MPC using a combination of RTP and CO_2 signals would shift consumption towards periods with a high share of wind power production. Finally, the ability of the MPC using RTP and CO_2 signals to flatten out load profiles, cutting off peaks, and induce a lower usage of non-RES was compared to more traditional space heating control systems.

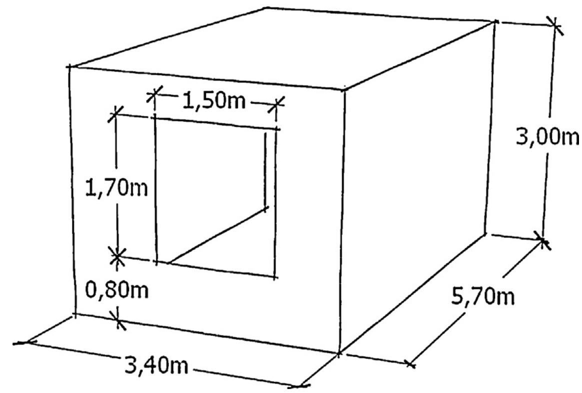

Fig. 1. Geometry of the EnergyPlus model (internal dimensions).

2. Method

The study reported in this paper is based on results from co-simulations of a test case modeled in EnergyPlus (EP) [22] and a heating system controlled by an MPC defined in MATLAB [23]. The EP model and the MPC are connected and exchange data in run-time via the Building Controls Virtual Test Bed [24,25]. The simulations are carried out for the period January 1 to February 14 in 2013 and 2014, respectively, which is within what is considered to be the general heating season in Denmark. The following sections explain the applied models in more details.

2.1. EnergyPlus model

The test case is featuring a dormitory apartment in the Grundfos Dormitory located in Aarhus, Denmark and modeled in EP. Fig. 1 shows the geometry of the apartment.

The model consists of a single thermal zone. All surfaces are internal and assumed to be adiabatic except for the south-facing wall which also has a low-energy window with no recess. The mechanical ventilation is always active with a constant airflow rate of 1.1 h^{-1} and a heat recovery of 75%. The infiltration rate is set to 0.05 h^{-1}. The heat source is assumed to be an electric baseboard with no thermal capacity. There are included no other internal heat loads to make the results easier to interpret. The Conduction Finite Difference algorithm is used to calculate the construction heat balances which induce the need for a small time step; we therefore apply 60 s time steps. The applied weather data is the EP weather file for Copenhagen [26]. Table 1 provides the details regarding the building constructions.