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Model predictive control for demand response of domestic hot water preparation in ultra-low temperature district heating systems

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ABSTRACT

In ultra-low temperature district heating the supply temperature is less than required to heat the domestic hot water and a heat pump is therefore often proposed to raise the temperature. This paper investigates how this heat pump can be utilized for price based demand response to induce peak reductions and energy cost savings. A model predictive control strategy is proposed and evaluated through co-simulations where a model predictive controller is formulated in MATLAB and connected to an EnergyPlus hot water storage tank. It is demonstrated that the system is capable of reducing the district heating morning peak and the electric grid evening peak as well as providing energy cost savings for the end-user without compromising hygiene and comfort.

1. Introduction

Demand response (DR) covers a range of measures designed to change the energy consumption pattern of the end-user in order to either improve the economic performance, reduce the environmental impact or increase the security of supply in an energy system. DR is often categorized according to the load shaping objective, i.e. load flattening, peak clipping or load shifting DR and often serve different purposes. The purpose of *load flattening* DR is to increase the utilization of high efficient baseload generation plants and reduce energy transmission losses. The purpose of *peak clipping* DR is to minimize the usage of inefficient and high pollutant peak plants and reduce needs for network investments. The purpose of *load shifting* DR could be to obtain a larger correlation between demand and energy price or demand and production from renewable energy sources [1]. Currently, the concept of DR is mostly considered in relation to the electricity grid but similar benefits can be obtained for district heating (DH) systems. For instance, a reduction of the DH morning peak can reduce the needs for investments in piping networks and peak plants or increase the security of supply [2–5]. Another example is for combined heat and power (CHP) plants which are connected to both the electricity and DH systems and can thus make profitable load shifting by planning their production with respect to the electricity spot market [6,7].

An important parameter in DH systems is the supply temperature. From the perspective of the end-user, it must be high enough to handle the demand for both space heating and preparation of domestic hot water (DHW). From an energy-efficiency point of view, it is desirable to have a supply temperature that is as low as possible in order to: minimize network loss; improve the efficiency of CHP plants or centralized heat pumps; enable the opportunity to integrate various renewable energy production and industrial waste heat in the DH system [5,8]. The supply temperature in DH systems is typically approx. 70–80 °C but it is possible to design or retrofit buildings to a level where the radiators or floor heating systems can maintain indoor thermal comfort with ultra-low temperature district heating (ULTDH), i.e. a supply temperature of 35–45 °C [8]. However, DHW must, for hygienic reasons, be at least 60 °C in the storage tank (if on the secondary side) and above 50 °C in circulation pipes [9,10] and DHW is therefore a main hindrance for immediate implementation of ultra-low supply temperatures in DH systems. One solution is to raise the DHW temperature in a dedicated DHW tank by means of a heat pump (HP) [8,11,12]. This setup also represents a potential DR resource applicable for both electricity and DH systems in that the HP draws energy from both systems and the tank temperature can thus be controlled according to both system needs. The overall DR potential is significant: preparation of DHW represents about 12% of the total energy consumption in the residential sector in the European Union [13] and 17.7% in the United States [14].

Other studies have introduced optimization-based control strategies aiming at minimizing energy consumption for DHW

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Nomenclature

T_{supply}	DH supply temperature (40 °C) [°C]
T_{main}	domestic cold water temperature (10 °C) [°C]
T_{hx}	HX outlet temperature (37.5 °C) [°C]
T_{room}	air temperature in the room of the ST (22 °C) [°C]
T_{out}	system outlet/supply temperature (55 °C) [°C]
T_{min}	lower bound on the average ST temperature (60 °C) [°C]
T_{max}	upper bound on the average ST temperature (95 °C) [°C]
ΔT_{hp}	temp. difference between the ST average and HP supply temperature (2 K) [K]
T_{bottom}	ST bottom node temperature [°C]
T_{hp}	HP outlet temperature [°C]
T_{avg}	ST average temperature across all nodes [°C]
T_{top}	ST top node temperature [°C]
ε	ST average temperature above lower bound (control variable) [K]
$\dot{m}_{top}$	water flow rate out of the ST top node [kg/s]
$\dot{m}_{p}$	water flow rate circulated by the CP [kg/s]
$\dot{m}_{out}$	water flow rate drawn by the end-user [kg/s]
$\dot{m}_{hx}$	water flow rate through the HX [kg/s]
P_{hp}	electrical power input to the compressor [W]
$P_{hp,max}$	upper bound on electrical compressor power (1700/3000 W) [W]
$\dot{Q}_c$	heat power delivered by the condenser [W]
$\dot{Q}_{draw}$	heat power drawn from the ST due to the tapping points [W]
$\dot{Q}_{loss}$	heat power lost from the surface of the ST [W]
$\dot{Q}_{hx}$	heat power transferred from the HX [W]
$\dot{Q}_e$	heat power absorbed to the HP evaporator [W]
η	ratio between actual COP and theoretical Carnot efficiency (0.23) [–]
C_{st}	thermal capacity of the ST [J/K]
c_p	specific heat capacity of water [J/kg K]
H_{st}	heat loss coefficient of the ST [W/K]
Δt	time step size (900 s) [s]
N	time steps in the prediction horizon (96 steps) [–]

preparation [15,16]. Halvgaard et al. [17] used an economic model predictive control (EMPC) to control an immersion heater installed in a hot water tank to support heat production from a solar thermal collector. The EMPC was able to generate cost savings by shifting the use of electricity according to a time-varying spot price. This paper proposes to apply an EMPC to control an HP used to raise the supply temperature in ULTDH since it can readily handle time-varying tariffs and different types of constraints. This paper also describes how the optimization problem can be formulated and solved by the EMPC. Finally, this paper presents the results of co-simulations that have been performed to investigate the DR potential of the proposed system. To the best of our knowledge, no previous studies have investigated this potential.

2. System design

Fig. 1 illustrates the proposed DHW preparation system consisting of a hot water storage tank (ST) connected to the DH system via a heat exchanger (HX) and an HP. The HX uses DH supply water with a temperature T_{supply} of 40 °C to increase the domestic cold-water temperature T_{main} from 10 °C to 37.5 °C before it enters the bottom of the ST. A circulation pump (CP) charges the ST by circulating water from the bottom of the ST across the HP to the top of the ST. The HP utilizes the DH supply water as a heat source to increase the temperature T_{bottom} to the HP outlet temperature T_{hp}. The system is connected to the electric system via the HP compressor that requires electric power P_{hp} to run.

An EMPC is used to control the HP and hereby provides DR by boosting the average tank temperature T_{avg} in periods with low energy prices and reduces consumption in high price periods in order to minimize total operating costs. The tank temperature could potentially become too high at tapping points and a mixing valve (MV) is therefore needed to ensure that the system outlet temperature T_{out} never exceeds 55 °C to avoid scalding at the tapping points (see Fig. 1).

The HP efficiency is described by the coefficient of performance (*COP*) defined as follows:

$$COP = \frac{\dot{Q}_c}{P_{hp}} \tag{1}$$

where $\dot{Q}_c$ is the heat power delivered by the condenser and P_{hp} is the electrical power input to the compressor. In this study, the *COP* was assumed a fraction η of the theoretical Carnot efficiency:

$$COP = \eta \cdot COP_{Carnot} = \eta \cdot \frac{(T_{hp} + 273.15)}{T_{hp} - T_{supply}} \tag{2}$$

The value of η depends on the specific HP, but this study applied $\eta = 0.23$ corresponding to COP ≈ 3.8 when $T_{hp} = 60$ °C and $T_{supply} = 40$ °C (Fig. 4 – left). The outlet temperature of the HP T_{hp} is controlled to be a fixed number of degrees ΔT_{hp} above the average tank temperature, which is obtained by adjusting the flow $\dot{m}_p$ circulated by the CP. We therefore have the following relationship:

$$T_{hp} = T_{avg} + \Delta T_{hp} \tag{3}$$

This study used $\Delta T_{hp} = 2$ K.

The flow $\dot{m}_{top}$ is controlled by the MV to obtain the desired system outlet temperature $T_{out} = 55$ °C. The resulting flow $\dot{m}_{top}$ is calculated as follows:

$$\dot{m}_{top} = \frac{(T_{out} - T_{hx})}{(T_{top} - T_{hx})} \cdot \dot{m}_{out} \tag{4}$$

where $\dot{m}_{out}$ is the total flow of hot water drawn by the end-user at the tapping points (draw profile).

3. Simulation method

The DHW preparation system described in Section 2 was studied through so-called co-simulations. An EnergyPlus (EP) [18] model of the system was coupled with an EMPC unit programmed in MATLAB [19] and they exchanged data during the simulation. The data exchange was handled by the building controls virtual test bed (BCVTB) [20,21]. Similar setups have been applied in other studies where building models were defined in EnergyPlus and coupled with advanced controllers defined in MATLAB [1,22–24].

Fig. 2 illustrates the setup and the exchange of data. The plant model (the system depicted in Fig. 1) was modeled in EnergyPlus and it represented the "true system". The plant model took compressor power P_{hp} as input from the MATLAB EMPC controller. In turn, it returned the average tank temperature T_{avg} as input to the EMPC. The EnergyPlus simulation time step was 60 s, but data and thus new control actions were only exchanged every 15 min.

There were thus two distinct dynamic models in this setup, namely:

(1) A detailed EnergyPlus *plant model* that represented the "true system".
(2) A simplified *control model* that was incorporated in the EMPC.

The ST was considered the only dynamic component in the DHW preparation system. The plant version of the ST was modeled in