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Optimal operation of energy storage in buildings: Use of the hot water system

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ABSTRACT

We consider the optimal operation of energy storage in buildings with focus on the optimization of an electric water heating system. The optimization objective is to minimize the energy costs of heating the water, with the requirement that we should satisfy the uncertain demand at any time. The main complications in this problem are the time varying nature of the electricity price and the unpredictability of the future water demand. In this paper we use the water heating system as an example for formulating a general framework which could easily be applied to similar problems with energy storage capacity. Feasibility and optimality are discussed and the main points are illustrated in the simulation case studies.

1. Introduction

Recently, considerable attention has been paid to renewable energy sources like wind turbines and photovoltaic parks. These alternative energy sources suffer a major drawback, however, due to their strong dependence on uncontrolled and varying weather conditions. This is an important limitation since the energy production is expected to cover the demand at any given time.

A possible approach for handling these fluctuations in the production is to shift the consumer load to periods where a lot of energy can be produced cheaply. This is referred to as demand side load management [1]. Field tests in the USA have demonstrated that such an optimization of domestic energy consumption can significantly reduce load peaks [2,3]. This can be achieved by manipulating the energy price according to demand information and weather forecasts. Electricity consumers are thus encouraged to consume electricity more prudently in order to minimize their electric bill. The dynamic energy pricing for demand load management is in itself a non-trivial problem and it is currently an active research area. The interested reader may check the literature [4–6] for more information, as this problem is outside the scope of this work.

Local energy storage in such setting provides several benefits for the consumer without having to adjust their consumption pattern. In particular, it enables

1. Higher peak capacity. For example, one may heat extra hot water in the morning to make sure there is enough water for everyone to have a shower.
2. Taking advantage of varying energy price. Energy can be purchased when prices are low and it can be used when the prices are high. (Since human users typically have a weak response to energy prices [7], automatically controlled consumers are better suited for a variable pricing scenario.)
3. Taking advantage of favourable outdoor conditions (e.g. cooling at night or heating during the day).

Energy storage devices could include hot water tanks, batteries, ice banks, liquid nitrogen, thermal storage building mass thermal capacity and compressed air storage [7].

Recently, there has been significant research activity around the problem of optimal usage of energy storing devices. For example, in [8] the problem of optimizing the end-consumer energy storage policies is considered. The proposed idea is to charge batteries when the electricity price is low and use the stored energy when the price is high. The authors show that the optimal policy has a simple structure based on two threshold levels: if the battery level is below a certain lower threshold value, the optimal policy is to charge it as close to the lower threshold value as possible. If the

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battery level lies above some upper threshold value then it is optimal to use the stored energy from the battery instead of purchasing from the grid. The difficulty lies in the computation of the optimal threshold levels which are a function of the varying energy price. However, analytical results can be derived for a few simplified cases, e.g. assuming perfect efficiency for charging and discharging the battery.

Ericson [9] presented results from a large scale Norwegian project where load control was applied on domestic hot water heaters. The main idea was to disconnect the water heaters from the electricity grid during peak hours in order to reduce the peak load. Electrical consumption of 475 households were investigated over a six month period from November 2003 to May 2004. The results show significant peak shavings in consumption during disconnection of hot water heaters. However, the researchers observed a considerable increased consumption after the reconnection of the heaters, which may have the adverse consequence of causing a new peak in the system.

Henze et al. [10] consider the optimization of the cooling system in commercial buildings. The authors propose shifting the thermal load by precooling the buildings structure at night, in addition to using *active* storage means such as ice thermal storage. The ultimate goal is to take advantage of ambient conditions and of real-time pricing to maximize the energy cost savings. The simulations show that the cost savings and on-peak demand reductions can be substantial (up to 57% and 50%, respectively) if a good model and accurate weather predictions are used.

Many recent contributions use model predictive control (MPC) solutions for this problem. In [11] a MPC controller is used to minimize a multi-objective function which trades off energy cost and comfort level in a dynamic real-time pricing scenario. They show that there is a good potential for savings compared to traditional control strategies. Not surprisingly, it is shown that the energy cost increases as the comfort level increases.

In this paper, we focus on the optimization of an electric water heating system which provides hot water for domestic usage. The optimization objective is to minimize the energy costs while obeying some operating constraints. The main idea is to use the heat capacity of the water tank to *store energy* in times when electric power is cheap and use it to match the demand when energy is expensive. The main contribution of this paper is to provide a systematic comparison between different strategies to operate the system. The idea here is to have a better understanding of the potential benefits of using energy storage in this problem. A comparison of the various strategies will be presented. We will distinguish between the following cases:

- *Ideal case*, where the optimal solution is computed assuming perfect knowledge of the future demand. This is a theoretical limit which cannot be achieved in practice, unless the future demand is known exactly.
- *Maximum storage policy*, where we maintain maximum storage in the tank at all times. This is achieved by fixing the tank temperature setpoint T_s and tank volume setpoint V_s at their maximum allowed value. This is the safest policy in terms of avoiding constraint violation caused by unforeseen high demand as it minimizes the risk of not having enough hot water.
- *Simple variable storage policy*, an intuitive money saving strategy in which we buy and store as much energy as possible during the night to be used during the day. The idea is to activate a 'storage mode' during night, when we set the energy storage setpoint E_s to its maximum, and a 'saving mode' during the day when we set E_s to a lower value. This policy is analogous to the work of [8], where the setpoint E_s plays the role of the switching threshold discussed in that paper.
- *Optimal variable storage policy*, where the temperature setpoint T_s and tank volume setpoint V_s are updated at every time step using a moving horizon optimization (MHO) approach. The optimization algorithm relies on a simple forecast model to predict the future demand. A detailed derivation of this method is presented in an accompanying paper [12].

Additional contributions of this paper include:

1. A detailed general problem formulation which may also be suitable for different applications involving dynamic optimization, energy storage and variable energy prices.
2. Guidelines about implementation strategies including control structures.

The paper is organized as follows: Section 2 presents the process modelling; Section 3 formulates the optimal control problem; in Section 4, insights into the implementation strategies are given; in Section 5 we detail different strategies for control and optimization of the system; Section 6 details a simulation study comparing various approaches. Section 7 presents a discussion on the subject and Section 8 concludes the paper.

2. Process model for hot water storage tank

The process we are dealing with consists of a heater which provides hot water for domestic usage. A simplified process flow scheme is shown in Fig. 1 where the important notation is presented. The system includes a cold water source, a thermally insulated tank, a heating coil with adjustable power and control valves that regulate the cold water inflow q_{in} and the hot water outflow q_{out}. A somewhat unusual feature of this system is that the hot water that leaves the tank (q_{out}) is mixed with a cold water stream (q_{cw}) from the same water source. This extra mixer is to allow extra flexibility and implies that the water in the storage

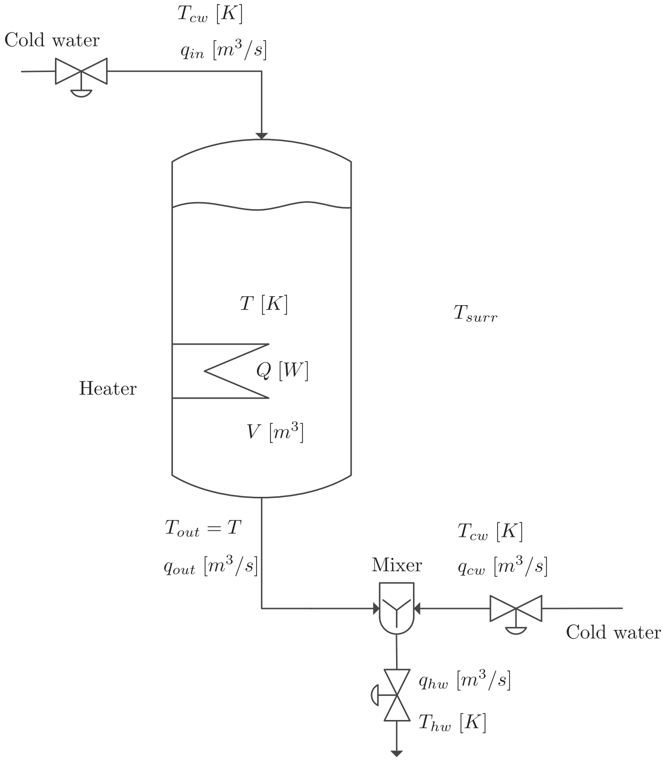

Fig. 1. Simplified process flow scheme.