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Hybrid model predictive control of stratified thermal storages in buildings

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ABSTRACT

In this paper a generic model predictive control (MPC) algorithm for the management of stratified thermal storage tanks in buildings is proposed that can be used independently of the building's heat/cold generation, consumption and consumption control. The main components of the considered storage management are the short term load forecasting (STLF) of the heat/cold consumer(s) using weather forecast, the MPC algorithm using a bilinear dynamic model of the stratified storage and operating modes of the heat/cold generator(s), modeled as static operating points. The MPC algorithm chooses between these operating modes to satisfy the predicted cold demand with minimal costs. By considering the generator(s) in terms of operating modes the bilinearity in the storage model is resolved which leads to a hybrid MPC problem. For computational efficiency this problem is approximated by an iterative algorithm that converges to a close to optimal solution. Simulation results suggest that the approach is well suited for the use in buildings with a limited number of heat/cold generators. Additionally, the approach is promising for practical use because of its independence from the heat/cold consumer's control and because it requires limited information and instrumentation on the plant, i.e. low costs for control equipment.

1. Introduction

The building sector accounts for up to 40% of total final energy consumption in developed countries [1] and therefore represents an important factor when trying to reduce global primary energy consumption. One of the possibilities for saving energy in buildings identified by [2] is to maximize the use of passive heating and cooling systems. However, since these systems are usually highly dependent on weather conditions and often produce heat/cold efficiently at low points of the building's energy demand, thermal storages become a necessity. Additional advantages of thermal storages are more viability towards renewable energy sources in the power grid and decreased energy costs due to the ability to exploit changing electricity rates via load shifting [3–5]. There are various kinds of thermal storages: passive storages such as the building structure itself or phase change material elements as well as active storages. At present the most commonly used active storage type in buildings is a stratified water storage tank, where the stratification is particularly important to increase passive heating/cooling efficiency [3].

The classic approach to controlling storage tanks is rule based control (RBC). While RBC is simple and easy to apply, these controls typically lack the ability for advanced storage management. Research into advanced control methods such as MPC in buildings has focused mostly on optimizing the entire building and especially exploiting the passive thermal mass of the building [6,7]. However, accurate models are necessary in order exploit these effects, which are very difficult to obtain [8,9].

Methods with active storages mostly relied on simple models of storage systems such as ice storages [10], batteries [11] or water storages with fixed temperature differences [12]. Research into the control of detailed models of stratified water storage tanks imposed strict assumptions on the storage tank and/or the heating/cooling systems. [13] considered the case of two separate layers in the tank, both with fixed temperatures and fixed return temperatures from the consumer and generation system. In [14] an integrated solution for a solar collector was developed, under the assumption that heating of the tank induced downwards flows, while cooling induced separate upwards flows in the tank. The on/off decisions for multiple chillers were discussed in [15] by assuming that the thermal storage is charged in the night and discharged during the day. The common assumption of these papers is that warm water always enters and leaves the storage tank at the top, while cold water is drawn from and supplied to the bottom. In [16,17] the inclusion of weather forecast to predictive control was investigated. While both

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stressed the importance of weather forecasts, the thermal storage tank models employed considered only a single temperature inside the tank, neglecting the important effect of stratification.

The predictive controller developed in this paper will focus on the control of an active water storage without requiring a model of the building. It will allow for general inflows/outflows to/from each layer of the storage tank from multiple sources while respecting the nonlinear dynamics of the storage tank. The goal is to create a modular storage management system that is operated with conventional heat/cold generation/consumption systems including their own separate (conventional) control. In order to be applicable generally only a reasonable set of sensors and actuators is used and the parameterization of the model is limited to key parameters of the storage tank.

The rest of the paper is structured as follows: the problem formulation is introduced in Section 2. Next the system is modeled and linearized in Section 3 and the controller is introduced in Section 4. Lastly simulation results are shown in Section 5 and conclusions are drawn in Section 6.

2. Problem formulation

In the following a cold storage tank is considered specifically, but the arguments and assumptions made remain valid when considering a storage for heat.

A possible configuration of the cold generation, storage tank and cold consumer is shown in Fig. 1. In the center one can see the storage tank. To the right there are generic cold consumers that can withdraw cold water from the storage tank at various layers and return warm water to other ones. To the left there are multiple cold generators which can withdraw warm water from arbitrary layers of the storage tank and return it as cold water. In the figure the simple case of cold water entering and leaving the storage tank at the bottom and warm water entering and leaving at the top is shown.

In order to ensure modularity of the control algorithm the cold consumers are not influenced directly by the storage management. This leaves the consumers' control as a problem to be solved on its own, but requires additional sensors to measure the consumed energy. Instead of modeling the consumer, the weather forecast is used together with short term load forecasting in order to predict future cold demand on the consumer side [18–20]. From STLF the mass flow in and out of the storage tank $\dot{m}_c$ and the warm water return temperatures T_c are obtained. These variables will usually depend on T, the temperature in the storage tank. In order to allow the consumer controller to be developed separately, it has to provide the storage management with setpoints for temperatures in the storage tank, T_{min} and T_{max}. These will serve as constraints for the controller.

For the controller the current temperature of the storage tank for every layer has to be known. Typically the model has more layers than temperature sensors so that state estimation becomes necessary. This is not the focus of the paper, but classic approaches such as extended Kalman- or particle filters are viable options. It is important that the sampling time of the state estimation algorithm is similar to the sampling time of the separate generation/consumption control, which is typically lower than the sampling time of the storage management.

The only output of the storage management controller to the system is to the cold generation control, where valves and pumps serve as actuators. For their control a model of the different generation devices is required, which will typically be nonlinear and

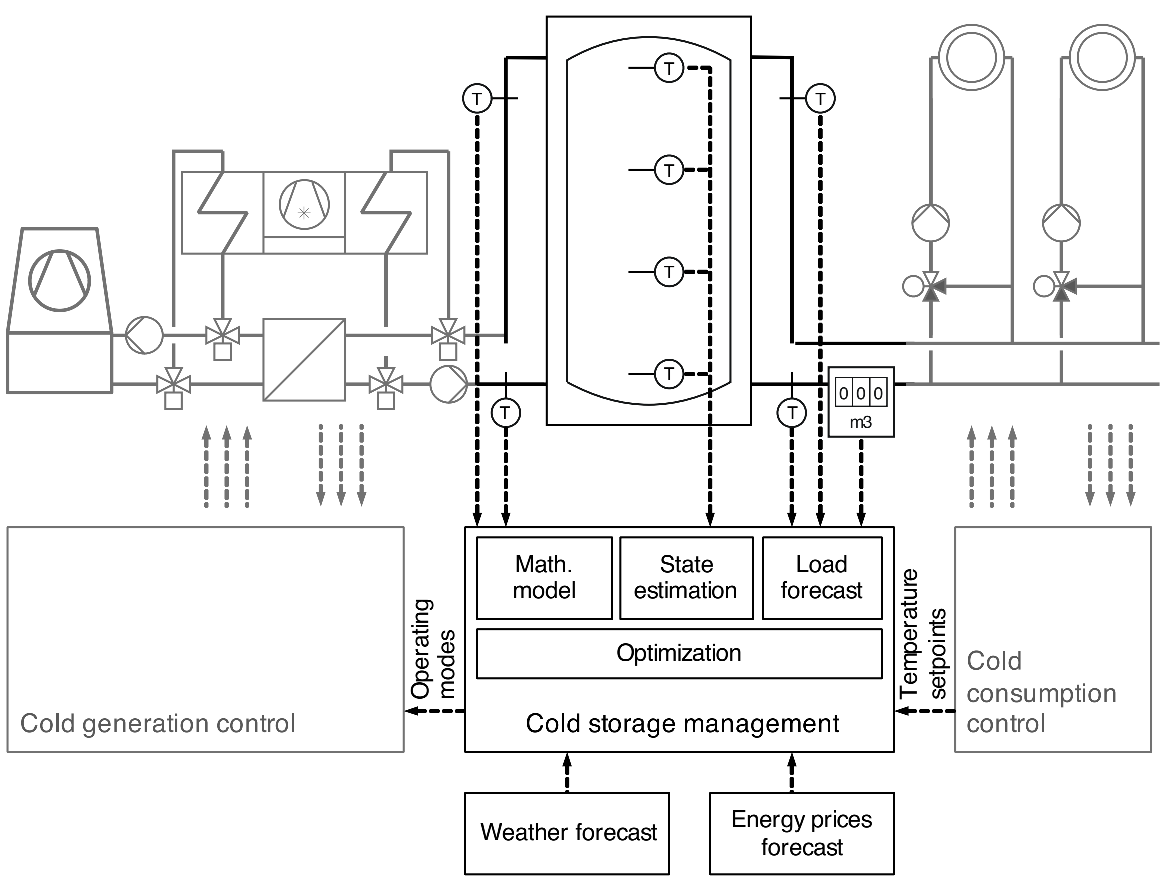

Fig. 1. The control scheme used by the MPC controller together with a possible setup. Left: cold generation; the cooling tower can be operated alone or in combination with the chiller. Center: stratified storage tank. Right: cold consumption; two cooling groups such as chilled ceilings in the building.