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Heiselberg, Per Kvols

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Application of Model Predictive Cold Storage Management in a Demonstrator Building

Markus Gwerder[1], Bruno Illi[2]

Building Technologies Division, Siemens Switzerland Ltd, Zug, Switzerland

[1]markus.gwerder@siemens.com

[2]bruno.illi@siemens.com

Abstract

The paper presents predictive cold storage management control algorithms for stratified cold water storages and their practical application in a demonstrator building. The demonstrator building energy efficiency center (www.energy-efficiency-center.de) is a research building in Würzburg, Germany, that implements novel, innovative and energy efficient materials, systems, and technologies. A generic algorithm for the management of stratified thermal water storage tanks in buildings based on model predictive control is investigated that can be used independently of the building's heat/cold generation, consumption and consumption control. For two different cold storage systems, the predictive cold storage management is applied both in simulation and in the demonstrator building. Its performance is compared to the performance of typical conventional non-predictive control. Simulation results show the superior performance of the predictive solution, while measurement results proof practical applicability of the predictive cold storage management solution. Compared to other model predictive control based approaches, the presented approach is promising for practical use because of its independence from the heat/cold consumer's type and control and because it requires limited information and instrumentation on the plant.

Keywords - building automation; predictive control; cold storage management

1. Introduction

The building sector accounts for up to 40% of total final energy consumption in developed countries [1] and therefore represents an important potential of global primary energy consumption reduction. 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]. There are different 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 for controlling storages 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 model predictive control (MPC) in buildings has focused mostly on optimizing the entire building and especially exploiting the passive thermal mass of the building [4]. However, accurate models are necessary to exploit these effects, which are very difficult to obtain [5].

In [6], a predictive controller was presented for the control of active water storage systems without requiring a model of the building. It allows for general inflows/outflows to/from each layer of the storage tank from multiple sources while respecting the nonlinear dynamics of the storage tank. Here, the application of this generic controller for two different cold management systems is presented, both in simulation and in practical application in a demonstrator building. The demonstrator is the research building energy efficiency center (see Fig. 1, www.energy-efficiency-center.de) in Würzburg, Germany, that implements novel, innovative and energy efficient materials, systems, and technologies, exemplarily demonstrating their applicability.

Fig. 1 The demonstrator building energy efficiency center (EEC) in Würzburg, Germany.

2. The Investigated Cold Storage Systems

The demonstrator building includes two cold generation and storage systems. Both systems include stratified thermal water storages of approximately 100 m^3 volume. The storages also serve as fire water tanks and are embedded in the ground near the building. While the first storage is cooled by a novel passive infrared night cooling (PINC) system, the second storage is cooled by a conventional chiller with the possibility of direct re-cooling. The chiller is a two-stage compression chiller with a net cooling capacity of 70 kW; the re-cooling unit (see Fig. 2 right) has a nominal thermal power of 90 kW and its fans are operated in two stages.

The cold consumption of the demonstrator building consists of 5 cold circuits: chilled ceilings, laboratory cooling, recirculation air fan coil units and three minor cold circuits. Only the chilled ceilings and laboratory cold circuits are supplied by the PINC cold generation. If the temperature provided by the PINC system is too high, these circuits can be supplied by cold from the chiller plant (as the other consumers).

In the PINC system, water from the top of the cold storage is pumped up to the roof of the building and sprayed on three slightly inclined fields (see Fig. 2) where the water flows down forming a thin water film. On its way over the field, the water cools down due to convection, radiation and evaporation. The cooled water then is feed back to the bottom of the storage. Compared to other passive cold generation systems such as cooling towers, PINC systems consume very low auxiliary energy (no ventilation necessary) and in particular make it possible to exploit the cooling potential during nights with clear sky due to radiation.

Fig. 2 Passive infrared night cooling fields (left), re-cooling unit and PINC fields (right).

3. The Investigated Cold Storage Management

The generic algorithm presented in [6] for the predictive management of stratified thermal water storage tanks in buildings based on MPC is investigated for both cold management systems introduced above. The main components of the considered storage management are the short term load forecasting of the cold consumption using weather forecast, the storage charge state estimation and the optimization algorithm using a dynamic model of the stratified storage and static model of the cold generation (see Fig. 3), represented as static operating modes. The optimization algorithm chooses between these operating modes to satisfy the predicted cold demand with minimal costs over the controller's prediction horizon (including forecast of energy prices).

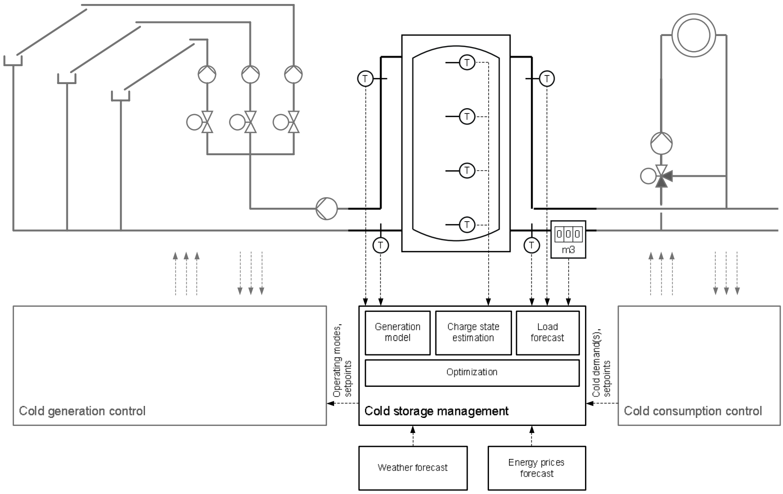

Fig. 3 The plant and control scheme used by the MPC controller for the PINC application. Left: PINC cold generation; center: stratified cold storage; right: cold consumption.

Short Term Load Forecasting

The investigated cold storage management does not directly influence cold consumption control. For consumption control, typical conventional control is used. The main task of the load forecast module is to predict future cold consumption given past consumption data as well as factors that are thought to influence future cold consumption and a forecast of how these factors will change in the future. The factors selected here were outside air temperature and solar radiation. For load forecast training, measurements taken from the building's weather station were taken; for forecasting, predictions from the German Meteorological Service (DWD) were incorporated. Load forecasting methods used here are based on support vector machine (SVM) learning techniques similar to [7].

Storage Charge State Estimation

In the demonstrator building, the cold storage charge state is estimated by using only the temperature measurements taken inside the storage at different heights. In case temperature measurements are not available from inside the storage in sufficient number, the charge state might be estimated by consideration of other information such as feed in/out water temperatures or eventually available flow measurements.

PINC Cold Generation Model

A PINC model can be found in [8]. For the application in the MPC controller, a static version of that model was deployed. For each PINC field, model parameters were tuned with measured data.

Chiller and Re-Cooling Unit Cold Generation Model

Direct re-cooling operation: In direct re-cooling operation, the chiller is turned off – the re-cooling unit directly provides cold to the storage via a heat exchanger, see Fig. 4. This operation is reasonable only if outside air temperature T_{Oa} is low enough. Heat exchangers were modeled by simple static models using the re-cooling number ε as single parameter, see (1), (2). This number represents how well the flow temperature on the side of interest reaches the returning source temperature, depending on the return temperature on the side of interest. Nominal re-cooling numbers can be found in heat exchanger data sheets or calculated from measured data, if available. The same simple model was also used for modeling the re-cooling unit, see (3). However, for that unit, the re-cooling number is set dependent on the unit's stage, i.e. dependent on the unit's fan speed.

$$T_{StIn} = T_{StOut} - \varepsilon_{Sec}\left(T_{StOut} - T_{rcOut}\right) \tag{1}$$

$$T_{rcIn} = T_{rcOut} - \varepsilon_{Prim}\left(T_{rcOut} - T_{StOut}\right) \tag{2}$$

$$T_{rcOut} = T_{rcIn} - \varepsilon_{rc}\left(T_{rcIn} - T_{Oa}\right) \tag{3}$$

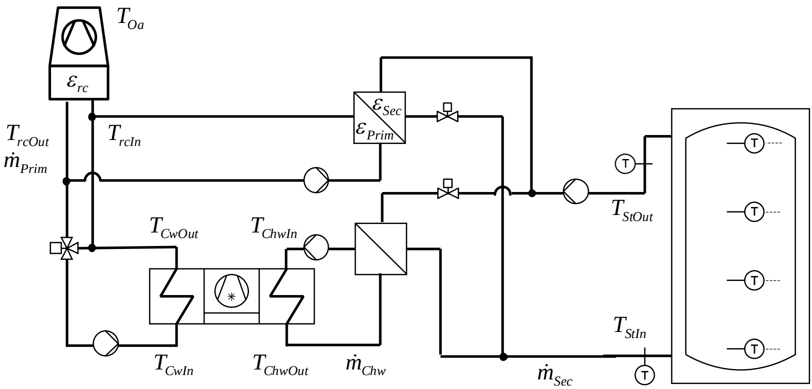

Fig. 4 Simplified plant scheme of cold generation by chiller and re-cooling unit.

Chiller operation: In chiller operation, the cold storage is cooled by the chiller (using the outside air as cold source via re-cooling unit). The principle assumption behind the chiller model is a constant ratio between the actual energy efficiency ratio (EER) and the ideal Carnot EER for both stages, cf. [9]. This ratio reflects the efficiency η of the chiller, see (4). Models used for the heat exchanger and re-cooling unit are as above.

$$\eta = \frac{EER}{EER_{Carnot}} = \frac{\dot{m}_{Prim} c_{Prim} (T_{ChwIn} - T_{ChwOut})}{P_{el}} \bigg/ \frac{T_{ChwOut}}{T_{CwIn} - T_{ChwOut}} \tag{4}$$

Optimization

The core of the cold storage management is an MPC algorithm that optimizes cold generation by numerical optimization. Over an optimization horizon (typically ≥ 1 day), the optimization computes the optimal operating mode sequence within the optimization horizon. See Table 1 as an example set of operating modes for chiller and re-cooling unit generation: Operating modes 1 and 2 represent direct re-cooling with different fluid mass flows; operating modes 3-6 represent chiller operation with different chiller stages and different fluid mass flows. Maintaining the storage temperature setpoint is implemented as a soft boundary condition for the optimization. Goal of the optimization is to minimize operation cost, e.g. monetary operation costs. Details of the optimization algorithm as well as the dynamic model for the stratified cold storage can be found in [6].

Table 1. Operating modes for chiller and re-cooling unit cold generation (example).

Operating mode	**1**	**2**	**3**	**4**	**5**	**6**
$\dot{m}_{Prim}$ [kg/s]	2.0	4.0	4.0	4.0	4.0	4.0
$\dot{m}_{Sec}$ [kg/s]	1.15	2.3	1.15	2.3	1.15	2.3
$\dot{m}_{Chw}$ [kg/s]	0	0	1.15	2.3	1.15	2.3
$P_{el,RC}$ [kW]	0.85 (st. 1) 1.7 (st. 2)	0.85 (st. 1) 1.7 (st. 2)	1.7	1.7	1.7	1.7
$P_{el,CH}$ [kW]	0	0	8.0	8.0	20.0	20.0

4. PINC System Results

Simulation Results

In simulation, only the chilled ceilings cold circuit was modeled, using a simpler hydraulic system than in the real building. Since monetary operation costs are typically very small compared to costs for maintenance, costs are assessed by operating hours (sum of all PINC fields). Operating hours are assumed to be an estimate of the maintenance costs which include costs such as replacing defect components or cleaning the fields and filters. Setpoint performance is assessed by integrating the deviation of bottom storage temperature from its setpoint over time. Here, the setpoint performance regarding a constant setpoint of 18°C for the cold storage bottom is assessed. However, it is not possible to always keep the cold storage ≤ 18°C since PINC is a free cooling system and cold consumption during summer leads to higher storage temperatures even when the storage is maximally pre-cooled from the start of the simulation. Nevertheless, such a setpoint performance indicator makes sense in terms of comparability between the different cases. Ultimately, the cold consumers have to be satisfied. Here, this means that the room temperature setpoint can be maintained in the simulated building. Since this not only depends on the provided cold storage temperature, but also on the (low-level) room temperature control, no room temperature setpoint performance criterion is applied.

Simulations were set up and executed in Matlab/Simulink. Using measured weather data and DWD forecast information from May 1st to October 1st 2014, simulation yielded 2136 hours of operation and a setpoint performance of 425 Kh for basic MPC configuration. Simulation of the same set-up using a conventional rule-based non-predictive cold storage control algorithm in basic configuration resulted in 2592 operation hours and a setpoint performance of 717 Kh. Operation hours for these two simulation cases are shown in Fig. 5. Results depend heavily on control configuration. However, for every rule-base control configuration case simulated, an MPC configuration was found that resulted in better performance for both criteria.

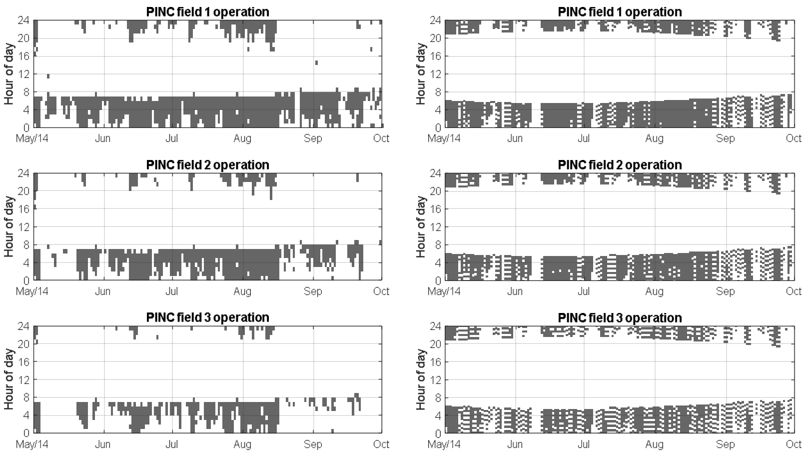

Fig. 5 Simulation results for PINC cold storage management; Operating hours for the 3 PINC fields marked gray for MPC (left) and conventional control (right).

Demonstrator Building Results

The presented MPC based cold storage management was activated on October 30th 2014 and successfully ran throughout the whole year of 2015. For demonstration, the same control code was executed as in simulation, connected to the building's automation system. Compared to the simulation, a lower storage setpoint of 14°C was used. Results for June 6st to June 26st 2015 are shown in Fig. 6. During the first days shown, the setpoint cannot be achieved – the PINC system is switched on whenever there is cold potential. From June 17th on, the system is able to exploit night-time phases with highest efficiency to reduce operating hours.

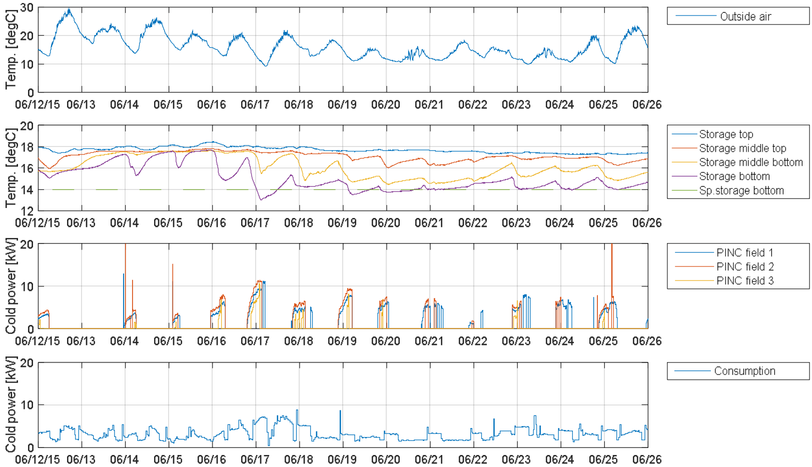

Fig. 6 Measurement results for PINC cold storage management, June 12th to 26th 2015.

5. Chiller and Re-cooling System Results

Simulation Results

A similar cold storage and consumption set-up was simulated as for the PINC system, except the following modification: Instead of only 10 rooms, the chilled ceiling cold group consisted of 150 rooms. Performance is assessed by monetary operation costs for electrical power. Cold generation operating modes as in Table 1 were applied. In basic configuration using a constant electricity price of 0.145 €/kWh, measured weather data and DWD forecast information from March 1st to October 1st 2014, simulation yielded monetary costs of 2289 € (see Fig. 7 for 9 days of operation). Simulation of the same set-up using a conventional rule-based non-predictive cold storage control algorithm with comparable setpoint performance resulted in monetary costs of 2507 €. The savings of 9 % when using the MPC storage management are moderate since there is not much optimization potential for the considered case with constant energy prices.

Introducing a high tariff phase each day from 6 a.m. to 9 p.m. where energy prices increase to 0.29 €/kWh, higher relative monetary cost savings result: 3533 € for MPC vs. 4372 € for RBC. In this comparison however, while the MPC strategy is fed with the energy prices information, the rule-based non-predictive strategy has no information about prices. Fig. 8 shows the same 9 days of operation for MPC with the varying energy prices. It can be clearly seen how phases with low energy prices are exploited.

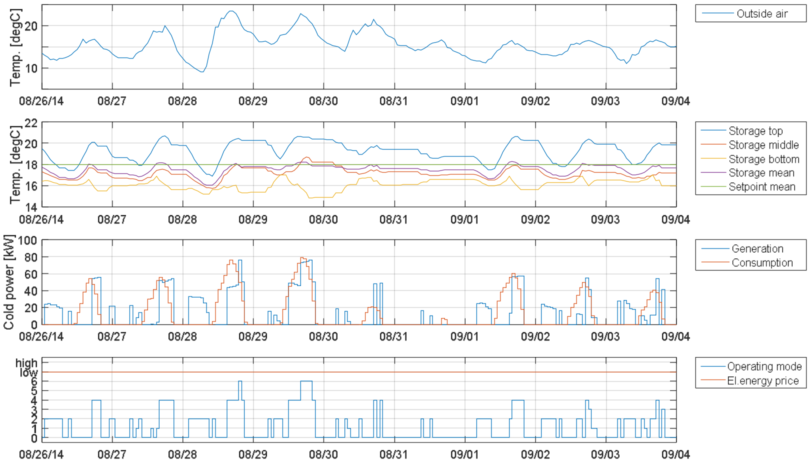

Fig. 7 Simulation results for chiller and re-cooling MPC cold storage management; constant energy price.

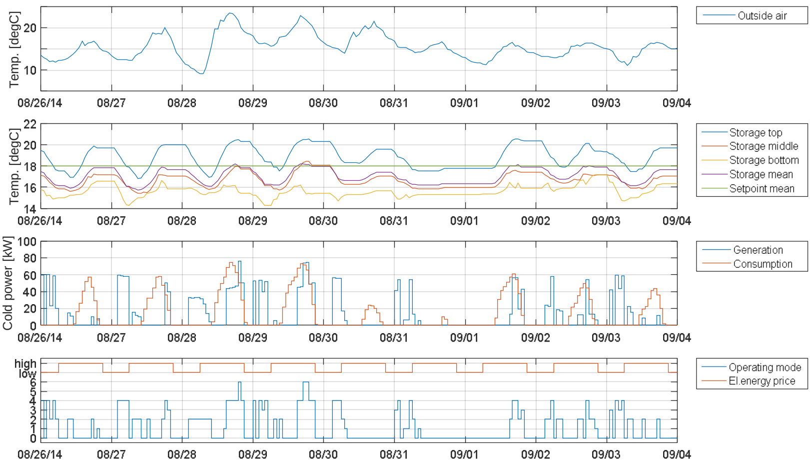

Fig. 8 Simulation results for chiller and re-cooling MPC cold storage management; varying energy price (low/high tariff).

Demonstrator Building Results

No demonstrator experiments results are presented here. At the time of writing this paper, experimenting is on-going. Meaningful results are expected in spring/summer 2016 (when cold demand increases).

6. Conclusions

The presented approach for predictive cold storage management was successfully demonstrated to be feasible both in simulation and in practical application in a demonstrator building. In an ideal setting, it can significantly increase performance of a storage system compared to typical conventional control. In addition – compared to other MPC approaches – the presented approach is promising for practical use because of its independence from the heat/cold consumer's type and control and because it requires limited information and instrumentation on the plant. However, consumption (control) that does not require unnecessary low cold water temperatures is precondition for efficient operation.

While additional costs for control equipment is low, engineering effort for the predictive MPC based solution is still higher than for typical conventional control, mainly because cold generation and storage systems typically are unique and therefore the model of MPC has to be adapted to each system individually. Potentially, this effort can be lowered on the one hand by using existing model components and on the other hand by automatically determine (some of the) model parameters.

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