Applied Energy 111 (2013) 1032–1045

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Model-based predictive control of an ice storage device in a building cooling system

J.A. Candanedo [a,*], V.R. Dehkordi [a], M. Stylianou [b]

[a] CanmetENERGY-Varennes, Natural Resources Canada, 1615 Lionel-Boulet, CP 4800, Varennes, QC J3X 1S6, Canada
[b] CanmetENERGY-Ottawa, Natural Resources Canada, 1 Haanel Drive, Building 5A, Ottawa, ON K1A 1M1, Canada

HIGHLIGHTS

- Simplified building linear thermal model obtained from building simulation model.
- Linear model used for the determination of required cooling power.
- Use of cooling power exchange as the basis for problem formulation.
- Focus on the optimal distribution of chiller/TES to supply cooling requirements.
- Significant cost reductions (5–30%) with respect to benchmark control strategies.

ARTICLE INFO

Article history:
Received 3 January 2013
Received in revised form 28 May 2013
Accepted 30 May 2013
Available online 22 July 2013

Keywords:
Model predictive control
Thermal energy storage
Ice storage
Simplified modelling
System identification
Building simulation

ABSTRACT

This paper describes an approach to the formulation of a model-based predictive control (MPC) algorithm for the cooling plant of a building under a time-dependent electricity price profile. The mechanical system includes a three-stage chiller and an ice bank used for thermal energy storage (TES). Cooling can be provided to the indoor space either by directly using the chiller or by discharging the ice bank when electricity prices are high. The chiller is also used to charge the ice bank at night. By applying system identification techniques, a simplified linear thermal model for the building was derived from a detailed building simulation previously developed in EnergyPlus. The use of a simplified linear model – along with weather and internal gains forecasts – allows to readily calculate the required cooling power for a given temperature setpoint trajectory. By making use of simple parametric models for the chiller and the ice bank, an optimization algorithm is applied to decide on the optimal combination of chiller and ice bank cooling power contributions at discrete hourly intervals over the prediction horizon. The length of the prediction horizon alternates between 24 and 30 h in order to coincide with the beginning or end of charge/discharge periods. The formulation of the optimization problem is considerably facilitated by using cooling power as the main working variable and then writing the equations accordingly. The proposed MPC strategy is compared with two rule-based control strategies: a modified storage-priority algorithm (similar to the one currently used in the case study building) and a chiller-priority algorithm. With the considered pricing structure and mechanical system, the MPC algorithm results in typical savings of about 5–20% with respect to the modified storage-priority strategy and about 20–30% with respect to the chiller-priority strategy.

1. Introduction

1.1. Background and motivation

This paper investigates an optimal control strategy for a cooling system in a small commercial building. The cooling system includes a chiller and an ice bank, which is used as a thermal energy storage (TES) device. With such a system, ice can be made (i.e., the ice bank is charged) when the cost of electricity is lower; the ice bank can supply cooling to the building (i.e., the ice bank is discharged) during peak hours, when the cost of electricity is higher [1].

The strategy proposed in this study, a model-based predictive control (MPC) algorithm, is aimed at finding the optimal combination of chiller and ice bank contributions that will provide the required cooling power at minimum cost within a time-dependent electricity profile. As its name indicates, MPC uses a model of the system, along with a forecast of the inputs, to select an optimal set of actions within a set of constraints (e.g., equipment capacity

* Corresponding author. Tel.: +1 450 652 3126.
E-mail address: jose.candanedo@nrcan.gc.ca (J.A. Candanedo).

0306-2619/$ - see front matter
http://dx.doi.org/10.1016/j.apenergy.2013.05.081

or operational constraints). As a subject of study in control engineering, MPC emerged in the late 1970s in chemical processing [2]. In heating, ventilation and air-conditioning (HVAC) systems, control techniques based on modelling, prediction and optimization have been investigated since the late 1980s [3–5]. Although the specific wording "model predictive control" has only been used in the context of HVAC applications in recent years [6–9], it is rapidly becoming more widely known [8,10,11].

Conventional building energy management usually relies on feedback and rule-based control [12]. With this approach, corrective adjustments are applied as a function of the "error signal", i.e., the difference between the current output and the desired value (Fig. 1a). When the mechanical system includes a TES device, a set of heuristic rules is used to decide whether the cooling/heating needs will be provided by the primary system or by the energy storage device.

In contrast with conventional control, MPC techniques (Fig. 1b) use a model of the system to predict the effect of disturbances (such as outdoor temperature and internal gains) and controllable inputs (such as heating or cooling rates). This information can be used to closely follow the setpoint, a difficult task in slow-responding, thermally massive buildings. Furthermore, MPC is considerably more beneficial when a TES device is used, since it allows optimizing its charge and discharge as a function of the expected cooling power load and energy cost profiles.

Today, MPC can be used to reduce operational costs in the presence of time-dependent electricity price profiles and demand charges. In the near future, buildings are expected to have a more dynamic interaction with the grid. Buildings will also face the challenge of incorporating new technologies, such as on-site renewable energy generation systems, new energy storage technologies and maybe even electric vehicles. In this context, advanced control strategies for managing the collection, storage and delivery of energy in buildings will play an increasingly significant role.

1.2. Objectives

The main objective of this study is to describe an innovative approach to the formulation of MPC in a building cooling system with a TES device. This study is intended as a step towards a systematization that will contribute to promote the use of MPC in buildings.

This paper focuses on finding the optimal mix chiller/ice bank for every time step over the prediction horizon. In other words, this study deals with the control of the charge and discharge of an active TES device (ice bank) for a given setpoint trajectory. The control of the passive TES (i.e., building thermal mass) by means of setpoint variation, while undoubtedly relevant, is beyond the scope of this paper.

The objectives of this paper are as follows:

- Discuss the development and application of a simplified linear thermal model derived from a building simulation model.
- Apply this simplified model to determine the required cooling power.
- Illustrate the use of the cooling power as the main working variable for the formulation of the MPC problem, while using simple models for the chiller and ice bank.

This paper presents the result of a simulation based on this method, and compares the performance of MPC with that of a more conventional rule-based approach.

1.3. Previous studies

1.3.1. Control strategies for cooling systems with ice storage

Ice storage systems have been used in buildings to shift peak loads and reduce costs for decades. Chapter 41 of the HVAC Handbook of Applications gives an overview of strategies used in the supervisory control of building cooling systems [13].

In existing cooling systems with ice storage, control strategies are often quite simple. For example, in the strategy called "chiller priority", the cooling load of the building is provided by a downsized chiller at all times as long as a given electric load limit is not exceeded; the rest of the time, the cooling load is provided by the ice bank [14]. Another strategy is the one denominated "storage priority". In a "storage priority" strategy, the chiller is used to make as much ice as possible during off-peak hours. The ice bank is used as the first priority to satisfy the cooling load. The chiller only provides cooling directly to the space when the capacity of the TES is exceeded.

It has often been pointed out that ice storage systems could significantly benefit from better control strategies [14,15]. The use of predictive control, and other optimal or near-optimal control techniques applied to the management of ice storage has been investigated [15–17]. Strategies coordinating the management of the building thermal mass and ice storage devices have also been studied [16,18,19]. For instance, Kintner-Meyer and Emery published one of the first studies on optimal control of a cooling system considering both the building thermal mass and a TES device [16].

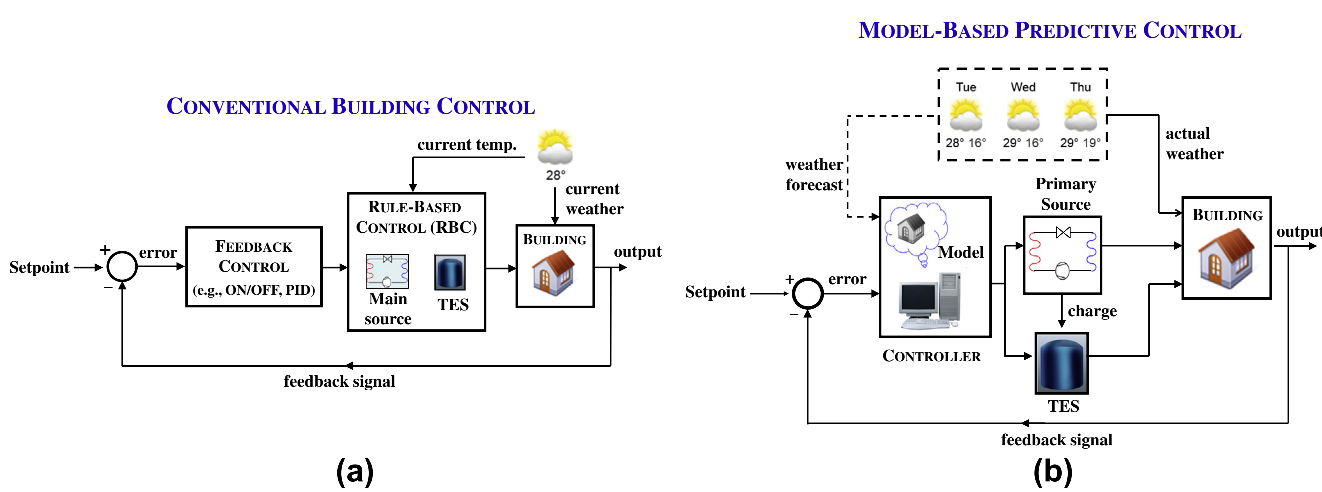

Fig. 1. Conventional control compared to MPC.