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Building Indoor Temperature Control Using Model Predictive Control in Cooling Systems

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Abstract: In this paper, an energy efficient temperature control algorithm with a photovoltaic (PV) system in cooling systems of a large glass-covered building is proposed using control horizon method. A control horizon switching method and linear programming algorithm is used for optimal control, and a time-of-use (TOU) electricity rate is included to calculate the energy costs. Simulation results show that the reductions of energy cost and peak power can be obtained using proposed algorithms.

Keywords: Energy saving, photovoltaic system, energy storage system, peak power reduction, model predictive control, building indoor temperature control.

1. INTRODUCTION

Temperature control in buildings has received much less attention from control engineering communities than other application fields like aerospace, petro-chemical, electronic or automotive industry. One of the reasons is that the effects of poor control cannot be easily noticed in temperature control of buildings. Therefore, buildings waste large amounts of energy due to poor control performance and have a potential for considerable savings by improving the control (Hazyuk et al., 2012a).

Nowadays the photovoltaic power generation capacity globally installed grows explosively as the capital cost of the photovoltaic power system reduces. And almost all of the photovoltaic power system is connected to the distribution grid. However, photovoltaic power generation is unstable, which is significantly affected by the weather and season. To improve the photovoltaic power utilization, the battery energy storage system (ESS) can be used to balance the differences between the photovoltaic power and peak power in cooling systems. The potential of PV systems in cooling systems is investigated by performing computer simulations for self-consumption and energy cost reduction (Bakos et al., 2003). The power demand for building indoor temperature control has a large overlap with photovoltaic power generation. An ESS is a system that is capable of absorbing energy, storing it for a period of time, and then returning it for use. In an electrical grid, an ESS can be used to match supply and demand. The ESS is charged when demand is low and discharged when demand is high. Thus, the overall energy efficiency of a system is improved, and the energy flow from the electrical grid connected to the system is stabilized. Installing an ESS can enable commercial to improve the quality and reliability of their power supply and to reduce their electricity costs (Barton and Infield, 2004).

Model-based control algorithms are desirable for both building designers and operators in that they can be simulated and tested even before a building is actually built. Moreover, an effective control system for one building is relatively easier to be adjusted and applied to another. Nowadays, time-of-use (TOU) electricity rates have been implemented on most smart grids for demand response. Significant potential savings have been shown by previous studies in model-based demand shifting and limiting control, through various simulations and field tests (Henze, 2005; Lee and Braun, 2008).

Model Predictive Control (MPC) has several features that make it suitable for the problems encountered in intermittently heated buildings (Hazyuk et al., 2012b). The MPC optimizes not only the comfort but also an energy usage. As heating systems generally consume energy to provide thermal comfort, MPC makes a trade-off between energy savings and thermal comfort. The MPC recently has been successfully applied on real occupied buildings (Kolokotsa et al., 2009; Vissers, 2011).

The paper focuses on the application of MPC to cooling systems that is charged on TOU rates. An MPC approach with linear programming (LP) algorithm is selected to model and simulate the cooling systems with ESS. An MPC strategy is selected, because its periodic re-optimization characteristic provides stability during external disturbances. The periodic re-optimization also compensates for inaccurate or simplified system models.

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2. ONE ZONE BUILDING MODELING

In order to formulate the reduced model of the building, models are represented in state-space by a set of first order differential equations. Moreover, the used MPC algorithm also requires the model of the system in the state-space representation. Low-order building models used for control purpose are most often derived from linear network representations with lumped parameters (Hazyuk et al., 2012a).

By covering a space with a glass skin, particular attention should be paid to the effects on indoor climate. In the hot season, the solar radiation both absorbed and transmitted by the glass sheet can overheat the underneath environment to temperatures which are incompatible with an acceptable thermal environment. The indoor climate depends on the external climate conditions, the building shape, type of building materials, internal heat gains and building systems like heating, cooling and ventilation. To get more feeling for different design parameters, the energy balance of a large glass-covered space will be discussed (Vissers, 2011).

The energy balance network of one zone building can also be shown in a simplified thermal network in Fig. 1. The resistances R in this network are equal to the thermal resistances of the building envelope and the capacitors C are equal to the thermal capacity (Incropera et al., 2006).

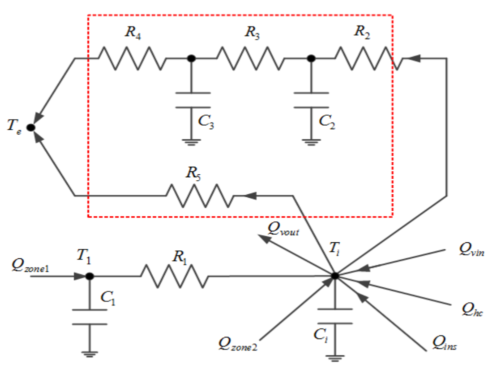

Fig. 1. Simplified thermal network of one zone building.

For the operating temperature range of the one zone building, the model is considered to be linear. In order to find the input-output equations for building from Fig. 1, the superposition theorem for electrical circuits is applied. For each mesh, different energy flows can be analyzed and written in a so-called ordinary differential equation. Thus, the following equation is obtained:

$$
\begin{aligned}
C_1 \frac{dT_1}{dt} &= \frac{T_i - T_1}{R_1} + Q_{zone} d_f \\
C_2 \frac{dT_2}{dt} &= \frac{T_i - T_2}{R_i} - \frac{T_2 - T_3}{R_3} \\
C_2 \frac{dT_2}{dt} &= \frac{T_i - T_2}{R_i} - \frac{T_2 - T_3}{R_3}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
C_i \frac{dT_i}{dt} &= Q_{hc} + Q_{ins} + Q_{zone}(1 - d_f) + \dot{m}c(T_e - T_i) \\
&\quad - \frac{T_i - T_1}{R_1} - \frac{T_i - T_2}{R_i} - \frac{T_i - T_e}{R_5}
\end{aligned} \tag{2}
$$

The output of the model is the indoor temperature. This temperature is influenced by four different inputs: ambient temperature (T_e), energy from building service (Q_{hc}), energy inflow by ventilation (Q_{vin}), and solar radiation (Q_{zone}). Thus, the following state space equation can be obtained (Boo et al., 2013):

$$
\begin{aligned}
\dot{x} &= Ax + Bu \\
y &= Cx
\end{aligned} \tag{3}
$$

$$
x = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_i \end{bmatrix}, \; y = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_i \end{bmatrix}, \; u = \begin{bmatrix} T_e \\ Q_{hc} \\ Q_{vin} \\ Q_{zone} \end{bmatrix} \tag{4}
$$

where x and y are the the state vector and the output of the system, respectively. T_1, T_2, T_3 and T_i are the internal mass temperature, internal surface temperature, external surface temperature and internal air temperature, respectively.

3. ENERGY EFFICIENT TEMPERATURE CONTROL CONSIDERING PHOTOVOLTAIC SYSTEMS

3.1 Minimal Energy Cost Function in Cooling Systems

In this paper, the potential of combining smart grid technology with ESS for utilizing PV power in cooling systems is investigated. This is done by creating a model of a microgrid containing a ESS with PV, building systems and a connection to the main grid. The day PV charging time is assumed from 7:00 am to 8:00 pm. The PV-installation provides electricity to ESS and the data predictions for 3kW PV generated power profiles per time-step are given by weather forecast in Fig. 2.

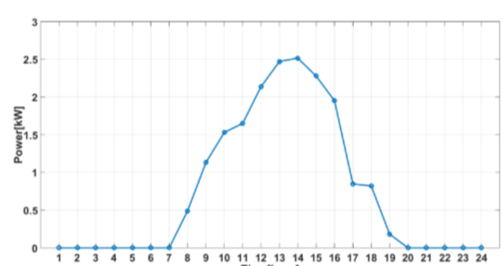

Fig. 2. Photovoltaic output power.

$E_{ess}(t)$ is the stored energy in ESS at time t and can be represented as

$$
E_{ess}(t) = E_{ess,init} + E_{pv}(t) - E_{cs}(t) \tag{5}
$$

where $E_{ess,init}$ is the starting stored energy in ESS by PV system at 9:00 am, $E_{pv}(t)$ and $E_{cs}(t)$ are the charging energy by PV generated power and the discharging energy by cooling systems from 9:00 am, respectively.

Since the purpose is to ensure thermal comfort with minimal energy consumption, the MPC cost function must reflect these performances in a mathematical formulation. Thus, the proposed cost function minimizes energy consumption,