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Control strategies for integration of thermal energy storage into buildings: State-of-the-art review

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ABSTRACT

Thermal energy storage (TES), together with control strategies, plays an increasingly important role in expanding the use of renewables and shifting peak energy demand in buildings. Different control strategies have been developed for the integration of TES into building-related systems, mainly including building envelopes, HVAC systems and hot water tanks (HTWs). A systematic survey of control strategies using TES in the building-related systems is still lacking. This paper presents a comprehensive review of these control strategies. It provides a summary of the applied strategies and makes recommendations for future studies. Considering that control techniques serve as a basis for the implementation of control strategies, typical control techniques utilized in the building systems, as well as their strengths and weaknesses associated with the application, are also introduced to help users gain a better understanding.

1. Introduction

Replacing conventional energy systems with renewables such as solar and geothermal energy is an efficient way to reduce dependence on non-renewable energy sources as well as greenhouse gas emissions. Although considerable effort has been devoted to addressing this issue, the main drawback of renewables' intermittence and variability in their availability remains one of the biggest barriers to building applications. This drawback might result in significant mismatches between the time of building energy demand and energy production. Bridging this gap calls for effective methods of incorporating thermal energy storage (TES) into buildings. TES allows energy to be stored when it is at its most abundant and to use it in time of need, and thus is well adapted for use with intermittent renewable energy sources. Similarly, by storing energy during periods of low demand and using it when the demand is high, it can be used to shift energy loads from the peak periods to the off-peak periods.

In the past several decades, many studies have been conducted to investigate the integration of TES into different building-related systems, mainly including building envelopes (e.g., wallboards, roofs and floors), HVAC systems (e.g., free cooling systems and central air-conditioning systems) and hot water tanks (HTWs). Both latent storage mediums like phase change materials (PCMs) and sensible storage mediums like building thermal masses have been used for such applications. In terms of the way to deliver thermal energy to the storage mediums, buildings integrated with TES (BITES) are generally classified into either active or passive systems. Active systems are defined as the one in which a fluid is circulated or electric heaters are used to exchange heat, while in passive systems no mechanical equipment is employed to deliver thermal energy [1–3]. For example, ice storage systems belong to active systems while building thermal masses (envelopes) are passive systems.

For BITES to reach their full potential, a key challenge to meet is the development of effective control strategies. Aiming at fulfilling building cooling and heating requirements, these strategies provide a flexible approach to integrating TES with other facilities, as well as responding to varying weather conditions, occupant behavior and utility rate structures. Despite playing a crucial role in system performance improvement and optimization, existing control strategies implemented in the buildings are insufficient for deriving benefit from TES. This highlights the need to examine existent strategies and properly address the issue of developing more advanced and efficient strategies. So far limited study has

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reviewed control strategies adopted in BITES. For example, Sun et al. [4] reviewed peak load shifting control strategies using cold TES facilities in commercial buildings. Pintaldi et al. [5] reviewed and evaluated control strategies for optimally managing TES for solar air-conditioning plants. ASHRAE [6] summarized different control strategies for centralized cooling and heating systems with and without TES, focusing on strategies associated with cost optimization. However, a systematic survey of control strategies for buildings integrated with TES is still lacking.

This paper presents a comprehensive review of the control strategies adopted for BITES by sorting BITES into three categories: active systems, passive systems, and combined systems (active & passive). The main goal is to provide a summary of these strategies and make recommendations for future studies. The target audiences are researchers, building designers and operators, system analysts and practitioners. Considering that control techniques serve as a basis for the implementation of various control strategies, typical control techniques utilized in BITES are also briefly introduced to help the target audiences gain a better understanding.

2. Control techniques utilized in BITES

Control techniques utilized in BITES are divided into different categories shown in Fig. 1 [7].

This section presents the control techniques and discusses their strengths and weaknesses associated with the application to BITES.

2.1. Classic local-loop control

Classic local-loop control techniques basically consist of on–off control and proportional-integral-derivative (PID) feedback control. On–off control techniques are used to control variables with discrete values such as on or off. Lin et al. [8] reported an application of on–off control when incorporating PCMs into building structures. They developed an under-floor electric heating system with shape-stabilized PCM plates in order to take advantage of night electric heating (i.e., 11 PM to 8 AM). Specifically, electrical heater is used to charge the PCM during the night and then to be released to the indoor air during the daytime. They established a prototype room to investigate its thermal performance. An on–off temperature controller was used to turn on the electric heater when its temperature was below 55 °C and turn it off when its temperature was more than 70 °C. The results show that this room was thermally comfortable and energy-efficient: more than half of the demand was shifted from the peak period to the off-peak period.

As the most ordinary but dominating type of feedback control, the principal objective of PID control is to minimize the “tracking error”, i.e., the difference between the desired set-point and measured process variable.

PID control was used to control temperature or flow rate in BITES both individually and combined with other control techniques. For example, Powell and Edgar [9] simulated a TES unit used in a concentrated solar power system in order to investigate the benefit of adding this unit. Two individual PID controllers were used: one to keep the output temperature of the solar power system constant and the other to keep the power output of the TES constant. The simulation results show that the whole system is able to provide constant power output despite the variability and intermittence in solar radiation’s availability. Mawire and McPherson [10] incorporated TES into a solar cooking system by charging the TES with a solar collector and then discharging its heat to the cooking system. The objective of this system was to maintain a nearly constant charging temperature not influenced by the variation of solar radiation, thereby efficiently transferring heat. In order to achieve this objective, they used a combined PID control and internal model control (IMC) structure which consists of an outer PID control loop and an inner IMC control loop. The PID loop is utilized to remove fast changing disturbances (e.g., power from the solar collector) beyond the IMC loop’s ability to process. The results show the efficient performance of the proposed control structure considering the charging temperature was maintained within a few degrees of the set-point.

The advantage of PID control lies in its intuitiveness and relative simplicity [11]. Also, no precise mathematical models of the control process are necessary. However, LeBreux et al. [12] reported that in many space heating applications, the PID controller is insufficient to control solar and electric energy storage. The main reason is that it tends to result in overheating due to its weakness in dealing with energy storage’s time evolution characteristics and in processing disturbance inputs. Moreover, PID controllers are normally used at the component level instead of the system level. It is seldom used independently when overall building performance is taken into consideration [13]. In addition, PID controllers need to be tuned for

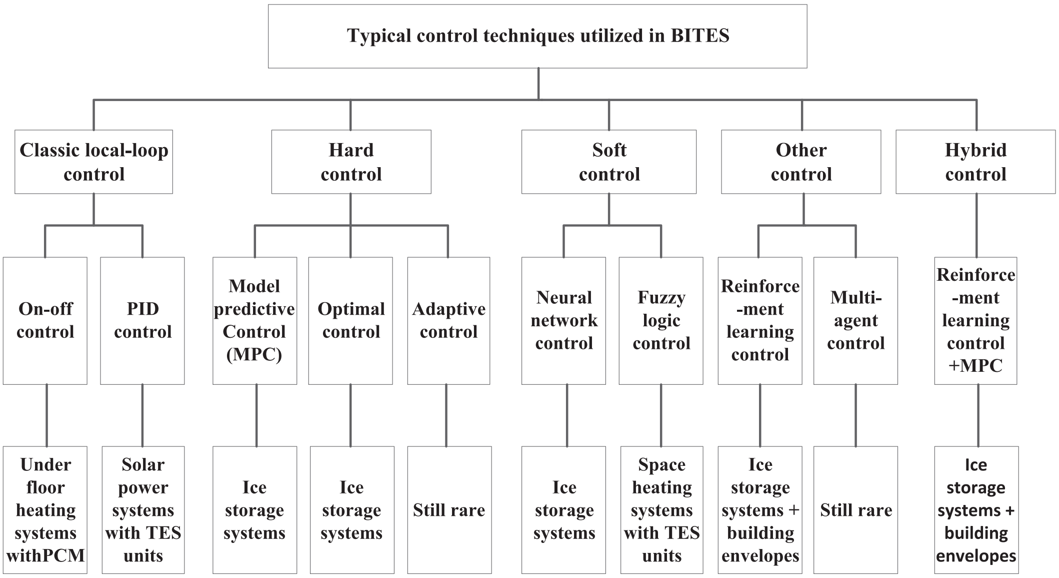

Fig. 1. Classification and typical applications of control techniques utilized in BITES [7].