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A review on optimization techniques for active thermal energy storage control

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ABSTRACT

The increasing popularity of smart energy systems has led to a gradual increase in the importance of thermal energy storage (TES) technology. Thus, the control strategy employed to efficiently take advantage of TES is expected to be very important. In other words, the time schedule, the particular components to be activated, and the amount of charging/discharging have to be appropriately determined. To date, a number of studies have investigated the optimization of TES operations by using optimization techniques. Current methods being used to achieve optimal TES operation are reviewed in this paper.

1. Introduction

With the recent growing awareness of global environmental issues and energy problems, smart energy systems based on different forms of renewable energy are attracting increasing attention. However, the temporal mismatch between energy supply and demand is one of the important challenges with which smart energy systems are confronted. Thermal storage systems designed to bridge this mismatch by removing heat from or adding heat to a storage medium for use at another time, and the thermal energy storage (TES) on which they depend, are therefore facing increasing expectations in terms of performance.

In addition, TES also plays an important role in increasing the overall system efficiency. A heat source machine is able to generate heat to meet demands at efficient partial load, because TES enables it to release heat during the daytime. The highest efficient load rate of many heat source machines shifts from rated load to partial load because the latest machines include inverters to enable them to vary their power output. Although TES is a significant technology, determining its optimal operation is not straightforward. The necessity to consider operation balancing, not only during a certain time interval, but also across whole time horizons, arises because of the capability of TES to transfer thermal energy from one time period to another, as mentioned above. Therefore, to date, a number of studies using optimization techniques to determine the optimal operational conditions have been conducted.

Previous papers in which optimal TES control has been reviewed include the following. Wang and Ma [1] provided the frameworks of control functions and optimization techniques for HVAC systems including TES control. Sun et al. [2] presented a classification of load shifting control and reviewed the present status of optimal control. Shaikh et al. [3] reviewed optimized control systems for building energy and comfort management. However, application of optimal techniques to active TES is still becoming more and more popular and a number of the techniques are increasing. It is useful for engineers and operators to clarify characteristic of each optimal technique proposed in the previous works. Thus, TES control techniques that are presently considered optimal are reviewed in this paper.

2. Overview of TES

TES is normally used for cooling or heating and stores heat during off peak periods for later use. That is, it discharges heat during peak energy use periods such that overall energy costs are reduced. These systems can either be “active” or “passive.” Passive TES refers to those systems that use some part of the building mass, or contents, to store heating or cooling capacity [4]. Active TES generates heat, which it then actively stores to a thermal storage material with the purpose of using the cooling and heating effect at a later time and differs from Passive TES in that it is

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Table 1
Summary of the studies that focused on active TES optimization control.

Ref.	Year	Case study	Storage type	Objective	Algorithm
[5]	1997	Office building	Ice storage	Operating cost	DP
[6]	2002	Office building	Cold water storage	Operating cost	OPTCON
[7]	2003	Office complex	Cold water storage	Operating cost	quasi-Newton method
[8]	2003	Simple-cooling plant	Ice storage	Operating cost	DP
[9]	2004	Office building	Passive thermal and cold water storage	Operating cost	quasi-Newton method
[10]	2005	Commercial building	Ice storage	Initial cost and Operation cost	DP
[11]	2006	Commercial building	Ice storage	Operating cost and energy consumption	Comparison of three cases
[12]	2009	Office building	Ice storage	Life cycle cost	PSO
[13]	2009	University Campus	Cold water storage	Operating cost	MINLP
[14]	2010	Hotel	Water storage	Combination of primary energy saving ratio, annual total cost and CO_2 emission reduction	PSO, GA
[15]	2010	Housing Complex	Water storage	Primary energy	MILP
[16]	2011	Hospital Building	Water storage	Operating cost	MINLP
[17]	2011	Power plant	Ice storage	Operating and capital cost	GA
[18]	2012	Laboratory test	Passive thermal and ice storage	Operating cost	The direct search complex method
[19]	2012	Office building	Passive thermal and ice storage	Operating cost	The direct search complex method
[20]	2012	Residential building	Water storage	Annual energy cost	GA
[21]	2012	Office building	Ice storage	Lifetime cost	MILP
[22]	2012	House, Industrial building	Water storage	The amount of energy exchanged by buildings and the electricity grid.	Fuzzy logic and Active set algorithm
[23]	2012	House	Water storage	Electricity charge, Electricity consumption, Surplus energy from PV, and Marginal fuel cost	MILP
[24]	2013	Commercial building	Battery storage, Water storage, Ice storage	Lifetime cost	MILP
[25]	2013	Commercial building	Ice storage	Operating cost	YALMIP
[26]	2013	Smart grid	Water storage	Total annual cost	EPoMP
[27]	2013	CHP-based micro grid	Battery storage, Water storage	Operating cost, Pollutant emission	MBFO
[28]	2013	District energy system	Water storage	Total investment and operating cost, Environmental impact	EP, MILP
[29]	2013	Office building	Water storage	Operating cost	Fuzzy, Predictive control
[30]	2013	Commercial building	Ice storage	Operating cost, System performance	GA
[31]	2013	Distributed energy system	Battery storage, Water storage, Ice storage	Total annual cost	MILP
[32]	2014	Distributed energy system	Water storage	Daily operating cost, Daily primary energy consumption	DP
[33]	2014	Distributed energy system	Aquifer thermal energy storage, Bore hole thermal energy storage	Total annual cost	MILP
[34]	2014	Building for commercial and industrial sectors	Thermal energy storage	Power system operating cost	Original
[35]	2014	Micro-grid	Water storage	Operating cost and pollutant emission	Original
[36]	2014	Housing complex	Water storage	Primary energy consumption	MILP

Abbreviations: DP: Dynamic programming, MILP: mixed-integer linear programming, MINLP: mixed-integer nonlinear programming, GA: genetic algorithm, PSO: particle swarm optimization, EP: evolutionary programming.

controllable. In this paper, we focus on the optimal control of active TES. TES is generally classified into three types: sensible heat storage (where heat is stored simply by changing the temperature of a material), latent heat storage (where heat is stored by changing the phase of a material), and chemical storage (where heat is stored in reversible, endothermic reactions and recovered by the corresponding exothermic reaction). Water is often used for thermal storage material because it is cost effective, readily available, has a relatively large heat capacity, and is neither toxic nor explosive. Moreover, ice has a relatively large latent heat of 335.2 kJ/kg compared to that of other thermal storage materials. Thus, both water and ice TES are widely used for air conditioning systems in general buildings.

3. Survey results for optimization control

The publications included in our literature survey are listed and briefly summarized in Table 1.

3.1. *Classification of control strategy*

The strategy we followed in this paper to classify TES control strategies follows that used in previous research [2,5] as shown in Fig. 1. The authors [2] modified the classification. Control strategies can be classified into heuristic and optimal control and in our work we focused on the latter.

3.2. *Objective functions*

According to the literature listed in Table 1, the objective of optimizing the TES control strategy is generally to minimize the operating cost, including both the energy cost and peak demand cost in many cases. This objective is described by the following equation [1,5]:

$$J = \min \left(\sum_{i=1}^{n} \alpha_i \times E_i + \beta \times \max_{1 \le i \le n} \left\{ \mathrm{PD}_i \right\} \right) \quad (1)$$