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Model-based optimization of ground source heat pump systems

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Abstract

This paper presents the development of an optimization strategy for ground source heat pump (GSHP) systems equipped with variable speed pumps in the ground loop system. The optimization problem is formulated using a model-based approach, in which the component models are used to estimate the system performance under various trial settings and an exhaustive search method is used to identify the optimal settings under the search ranges defined. The variable optimized is the outlet water temperature from the ground heat exchangers, which can be used as a set-point to control the operation of the variable speed pumps in the ground loop system. The overall objective of the optimization is to minimize the system power consumption while providing required building heating and cooling demand. The performance of the proposed strategy is tested and evaluated through simulations. It is shown that, compared to a two-stage control strategy for variable speed pumps, the proposed strategy can save 4.2% of cooling power consumption of the GSHP system studied. The methodology used in the development of this proposed strategy can be potentially useful for control optimization of any types of GSHP systems. For complex systems, a performance map can be generated based on this method and then used to practically control the operation of GSHP systems.

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Keywords: Control optimization; Model-based approach; GSHP systems; Variable speed pumps

1. Introduction

Ground source heat pump (GSHP) systems have attracted increasing attention due to their high energy performance and are being recognized as one of the most sustainable systems for heating and cooling of both residential and commercial buildings [1, 2]. The performance of a GSHP system is influenced by many variables such as the type of GSHP systems, ground heat exchanger (GHE) configuration, soil conditions, building load characteristics, equipment selection, system sizing, control optimization and local climate [3-5].

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Over the last several decades, many efforts have been made on appropriate design and optimal sizing of GSHP systems. Nagano et al. [6], for instance, presented the development of a design and performance prediction tool for GSHP systems. Sivasakthivel et al. [7] employed Taguchi and utility methods to optimize GHEs used for space heating applications. Li and Lai [8] applied the entropy generation minimization method to optimize the design of a vertical GHE. A multi-objective design optimization strategy for vertical GHEs was presented in [9] to minimize the system upfront cost and entropy generation number. The results from these studies showed that appropriate design of GSHP systems is essential to reduce their installation cost and lifetime operational cost.

Besides appropriate design, control and optimization of GSHP systems are also important to improve their operating efficiency while providing satisfied indoor thermal comfort. Through experimental investigation, Zhai et al. [10] concluded that optimization of indoor temperature settings can alleviate the thermal imbalance of the ground, which would be beneficial to the long-term operation of GSHP systems. Zhu et al. [11] reported the use of improved control strategies to select the operation modes of a ground water-source heat pump system. Gang et al. [12] investigated the performance of a GSHP system coupled with a supplemental heat rejecter by using a schedule based control, temperature differential based control and artificial neural network (ANN) based predictive control, respectively. The result showed that ANN-based predictive control is more energy efficient. The use of intermittent operation strategies for a hybrid GSHP system with cooling towers was studied by Yang et al. [13]. The simulation results showed that the proposed strategies can alleviate the soil heat accumulation and reduce the energy consumption of the hybrid GSHP system. Yavuzturk and Spitler [14] presented a comparative study of the control strategies for supplemental heat rejecters used in hybrid GSHP systems. It was shown that the best control strategy investigated was to operate the supplemental heat rejecters based on the difference between the fluid temperature exiting the heat pumps and ambient air wet-bulb temperature. An optimization methodology for frequency control of variable speed water pumps in GSHP systems was presented in [15]. The overall methodology consists of three steps, including frequency tests, system COP maps, and system performance factor maps. The results indicated that up to 32% energy savings can be achieved by using this optimization methodology. The above studies showed that proper control of GSHP systems is essential to substantially reduce the operational cost of GSHP systems. However, the research in this area is far from sufficient compared to the research on design optimization and optimal sizing of GSHP systems.

This paper presents an optimization strategy for optimal control of GSHP systems equipped with variable speed pumps in the ground loop system. The optimization strategy is developed using a model-based approach. The overall objective of the optimization is to minimize the total energy consumption of the heat pumps and the water pumps in the ground loop system without sacrificing the indoor thermal comfort and violating the relevant operating constraints.

2. Model-based optimization strategy

2.1. Outline of the optimization strategy

The proposed optimization strategy for GSHP systems is illustrated in Fig. 1. It is developed based on an assumption that a variable speed pump(s) is installed in the ground loop system to modulate the water flow rate. The overall optimization process consists of two steps. The first step is to use a rule-based sequence controller to determine the operating number of the heat pumps based on the building heating/cooling demand and the capacity of each heat pump as well as the operating constraints of practical applications. The second step is to determine the optimal combination of the outlet water temperature from the GHEs (i.e. the inlet water temperature to the source side heat exchangers of the heat pumps) and the water flow rate circulating through the GHEs to minimize the total power consumption of the water pumps in the ground loop and the water-to-water heat pumps. This is achieved by using a model-based approach, in which the simplified component models of heat pumps, water pumps and GHEs are used to predict the performance of the GSHP system under different trial settings of the optimization variables and an exhaustive search method is used to search for the optimal solutions of the optimization problem. For a given trial combination, the water-to-water heat pump model is first used to determine the power consumption of the heat pumps and the outlet water temperature from the source side heat exchangers of the heat pumps. This temperature is then used as the inlet water temperature of the GHEs. Using the GHE model and water pump models, the outlet