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Modeling and optimization of a chiller plant

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A B S T R A C T

A data-driven approach is utilized to model a chiller plant that has four chillers, four cooling towers, and two chilled water storage tanks. The chillers have varying energy efficiency. Since the chiller plant model derived from data-driven approach is nonlinear and non-convex, it is not practical to solve it by using the traditional gradient-based optimization algorithm. A two-level intelligent algorithm is developed to solve the model aiming at minimizing the total cost of the chilled water plant. The proposed algorithm can effectively search the optimum under the non-convex and nonlinear situation. A simulation case is conducted and the corresponding results are discussed.

1. Introduction

A chiller plant normally consists of chillers, cooling towers, pumps and chilled water storage tanks. It is frequently used to air conditioning large office buildings or campuses with multiple buildings [1]. More than 40% of the total electricity in a building is consumed by the chiller system. Thus effective energy management of chiller plants is becoming important to save energy consumption and reduce environmental impact [2].

Managing a chiller plant is a complex and challenging task. Many work and research have been reported in literature for optimizing one of the components in a chiller plant [3–8]. For example, Chan and Yu developed a chiller model based on a simulation program [9]. Optimum set point of condensing water temperature for chillers was found and controlled to reduce fluctuation in chiller efficiency in different operating conditions. Fisenko et al. [10] presented a mathematical model of a control system of the mechanical draft cooling tower. The control system was able to optimize the performance of the cooling tower under changing atmospheric conditions. Mathematical models associating with cooling loads and energy consumption were established by Lu et al. [11] to calculate optimal set points based on sensor information. Operating the chilled water system at optimized chilled water supply temperature, chilled water pump head and other set points was found with significant reduction in energy consumption.

For the chiller plant having multiple chillers, not all chillers are running at the same time. Optimal sequencing chillers can improve energy efficiency of the chiller plant [12–14]. Chang [15–17] used different methods to search optimal chiller sequence, such as dynamic programming, neural networks, branch and bound method. The results indicated that energy savings can be obtained simply by changing chiller sequences. A robust chiller sequencing control strategy was proposed by Huang et al. [18] for central chiller plants. Data fusion scheme and fault detection and diagnosis scheme were developed to improve the reliability. The control strategy was validated by the dynamic simulation of the central chiller plant.

For those improvements based on optimization of single component of a chiller plant, the interactions among components are neglected. In fact, a chiller plant is a system in which components affect and are affected by the operation of the plant. In addition to equipment themselves, many other factors influence chiller plant's energy consumption. Such factors include weather, number and type of operating time, building use and cooling loads [19]. It is critical to consider the interactions and factors when managing a chiller plant to improve the energy efficiency.

In this paper, a chiller plant that has four chillers, four cooling towers of varying energy efficiency is considered. The plant also has two chilled water storage tanks that can be used to store the chilled

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water under the following two cases: first, the plant can produce more chilled water when the electricity price is low; second, the plant can produce more chilled water when the demand is not high and this excessive chilled water can be used when the demand is more than it can produce. A data-driven approach [20–22] is employed to model this plant based on the dataset collected from the historical operation of this plant. Since the model derived from data-driven approach is nonlinear and non-convex, the traditional gradient-based optimization algorithm cannot solve it efficiently. Thus, a strengthened genetic algorithm is designed to solve the model aiming at minimizing the total cost of the chilled water plant. A simulation case is conducted in the last section and the corresponding results are discussed.

2. Chiller plant modeling

2.1. Chiller plant description

Fig. 1 illustrates the schematic diagram of a typical chiller plant. The chiller plant is usually consisted of chillers, cooling towers, condensing water pumps, chilled water distribution pumps, chilled water storage tanks, and distribution pipes. The chillers in the plant can be connected in series or in parallel. The components that consume energy in the chiller plant include chiller compressors, cooling tower fans, condensing water pumps, and chilled water distribution pumps. A chiller plant that includes four chillers and four cooling towers connected in parallel is considered in this research. In addition, the plant has two chilled water storage tanks that can store excess chilled water when electricity price or demand is low. The stored chilled water can be used when electricity price or demand is high. By using the chilled water storage tanks, the cost of the plant can be saved. Fig. 2 shows a fluctuated hourly electricity price in a typical day. Thus an operation schedule of the chiller plant could be arranged over a demand period to minimize the total cost. Fig. 3 shows a chilled water demand for one typical day. To make the system simple, energy consumption of the pumps is not considered since it only accounts for a small part of the total energy consumption of the entire system. Assume that the energy consumed by unit i (a chiller and a cooling tower) at time t is u_{it}. Also, the electricity price at time t can be expressed as p_t. A decision variable x_{it} is introduced to turn on or turn off chiller i at time t for the following reason: The four chillers have different energy efficiency. Therefore it is necessary to decide which chiller should be used when the plant does not need to turn on all chillers. Thus, the total cost of the plant over one period (T) can be expressed as Eq. (1):

$$P_{\text{total}} = \sum_{t=0}^{T}\left(p_t \sum_{i=1}^{N} u_{it}\cdot x_{it}\right) \quad (1)$$

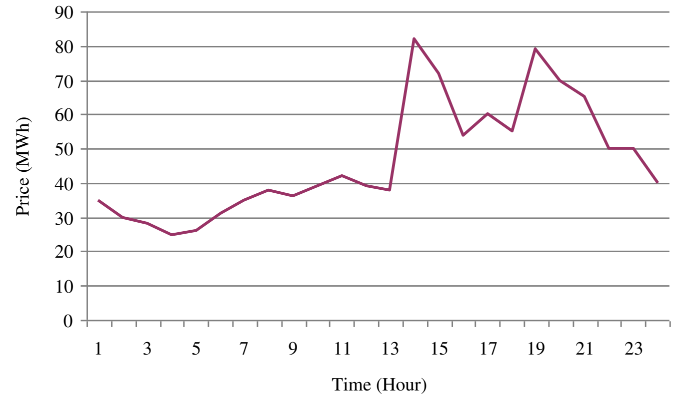

Fig. 2. The fluctuated hourly electricity price in a typical day.

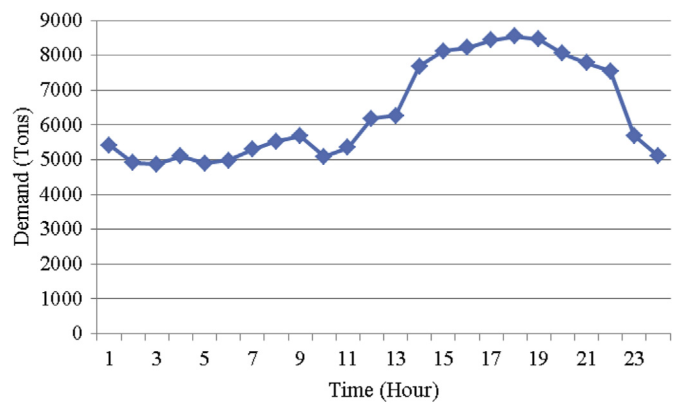

Fig. 3. The demand of cooling load in a typical day.

where P_{total} is the total cost of the plant, N is the number of the chillers.

The goal of this research is to minimize the total cost of the chiller plant. To achieve this goal, a schedule over a demand period to control the chillers should be made first and then two controllable variables of each chiller should be set at each time set p. The two controllable variables are chilled water flow (q_{it}) and the temperature difference of the condensing water (Δt_{it}). Thus, it is necessary to model the energy consumption for each unit. A data-driven approach is employed to build the model and the corresponding conceptual data-driven expression is presented in Eq. (2):

$$u_{it} = f_i(q_{it}, \Delta t_{it}, h_{t-1}) \quad (2)$$

Where h_{t-1} represents the enthalpy of ambient air at time step $t-1$.

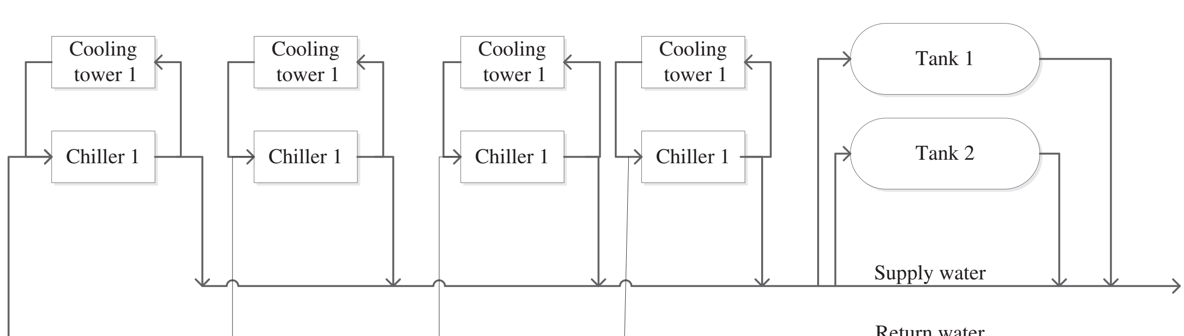

Fig. 1. Schematic diagram of a typical chiller plant.