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Amelioration of the cooling load based chiller sequencing control

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HIGHLIGHTS

- We developed a new approach for the optimal load distribution for chillers.
- We proposed a new approach to optimize the number of operating chillers.
- We provided a holistic solution to address chiller sequencing control problems.

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ABSTRACT

Cooling Load based Control (CLC) for the chiller sequencing is a commonly used control strategy for multiple-chiller plants. To improve the energy efficiency of these chiller plants, researchers proposed various CLC optimization approaches, which can be divided into two groups: studies to optimize the load distribution and studies to identify the optimal number of operating chillers. However, both groups have their own deficiencies and do not consider the impact of each other. This paper aims to improve the CLC by proposing three new approaches. The first optimizes the load distribution by adjusting the critical points for the chiller staging, which is easier to be implemented than existing approaches. In addition, by considering the impact of the load distribution on the cooling tower energy consumption and the pump energy consumption, this approach can achieve a better energy saving. The second optimizes the number of operating chillers by modulating the critical points and the condenser water set point in order to achieve the minimal energy consumption of the entire chiller plant that may not be guaranteed by existing approaches. The third combines the first two approaches to provide a holistic solution. The proposed three approaches were evaluated via a case study. The results show that the total energy consumption saving for the studied chiller plant is 0.5%, 5.3% and 5.6% by the three approaches, respectively. An energy saving of 4.9–11.8% can be achieved for the chillers at the cost of more energy consumption by the cooling towers (increases of 5.8–43.8%). The pumps' energy saving varies from −8.6% to 2.0%, depending on the approach.

1. Introduction

1.1. Background

In the United States, commercial building cooling equipment consumed around 77.4 GWh primary energy in 2010 [1]. Chiller plants are widely used to provide cooling for commercial buildings. As major components of the chiller plants, chillers alone represented about 35% of the energy consumption by the commercial building cooling [2]. Due to their significant energy consumption, optimal control of chiller plants is of great interest to the nation. To enhance the operational efficiency of chiller plants, many researchers have devoted efforts to achieve the optimal control of the plants. As a result, many approaches have been proposed [3–43].

Among various configurations of chiller plants, multiple-chiller plants are the most widely used. For those plants, it is recommended to operate chillers sequentially rather than simultaneously [44]. To operate chillers in sequence, one uses a chiller sequencing control, usually based on the cooling load, to bring chillers online or offline. Depending on the approach to indicate the cooling load, the chiller sequencing control can be categorized as: the return chilled water temperature based control, the bypass flow based control, the direct power based control, and the Cooling Load based Control (CLC) [45]. Among them, the CLC is considered to be the most promising because other approaches employ the use of indirect indicators of the cooling load (e.g. the return chilled

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water temperature, the volume flow rate at bypass of secondary loop, and the chiller power), which may not be proportional to the cooling load [21]. The CLC directly calculates the cooling load using the chilled water flow rate and the difference between the chilled water supply temperature and return temperature [9].

In the CLC, one chiller will not be brought online/offline unless the cooling load is larger/smaller than the total available cooling capacity of operating chillers. The total available cooling capacity of i operating chillers can be referred as a Critical Point (CP):

$$CP_i = \sum_{j=1}^{i} CC_{act,j}, \tag{1}$$

where $CC_{act,j}$ is the actual cooling capacity of the jth chiller. In the real world implementation, the nominal capacity of the chiller, $CC_{nom,j}$, is conventionally used to represent $CC_{act,j}$. Thus, Eq. (1) can be converted into:

$$CP_i = \eta \sum_{j=1}^{i} CC_{nom,j}, \tag{2}$$

where η is the safety factor (e.g., 90%) to mitigate the risk of insufficient cooling supply during the chiller start-up period. Besides, a state machine [46] can also be used to facilitate the implementation of the CLC. To avoid a chiller short circling, a waiting time t_{wait} and a dead band CP_{db} are usually employed. For instance, Fig. 1 shows a conventional CLC for a chiller plant with three identical chillers. The transition between states indicates adding or reducing the number of operating chillers.

1.2. CLC optimization

Although widely used, the conventional CLC has limitations and can't guarantee the minimal energy consumption by chiller plants. To improve the energy efficiency of chiller plants, researchers proposed various CLC optimization approaches [5–7,9,20–33,40–43]. Generally speaking, those approaches can be divided into two groups: studies to optimize the load distribution and studies to identify the optimal number of operating chillers. We will discuss the concept and limitations of each group as follows.

The first group aims to optimize the load distribution among the chillers. The conventional CLC turns on an additional chiller only when the cooling loading approaches the total nominal cooling capacity of operating chillers. This means that chillers will work at the highest Partial Load Ratio (PLR). The PLR is the ratio of the cooling load handled by one chiller to its nominal cooling capacity. However, the ASHRAE Handbook [44] points out that a higher chiller PLR does not necessarily mean a higher operational efficiency. The chiller's operational efficiency is usually measured by the coefficient of performance (COP), which is the ratio of the cooling energy provided by the chiller to its power consumption. Fig. 2 shows that the highest $COPs$ may occur at relatively low $PLRs$ for three different chillers.

To achieve the optimal load distribution, researchers developed model based optimization approaches to adjust the PLR of each chiller individually according to a given cooling load [5,7,22–33]. Some studies aimed to maximize a summation of operating chillers' COP as follows [5,22,24,33]:

$$J = \max\left(\sum_{i=1}^{M} COP_i\right), \tag{3}$$

s.t.

$$\sum_{i=1}^{M} PLR_i CC_{nom,i} = \dot{Q}, \tag{4}$$

where COP_i and PLR_i are the COP and PLR of the ith chiller, respectively. The M is the number of the chillers in the chiller plant and $\dot{Q}$ is the cooling load. They utilized a regressed PLR–COP curve in Eq. (5) to calculate the COP_i under the PLR_i:

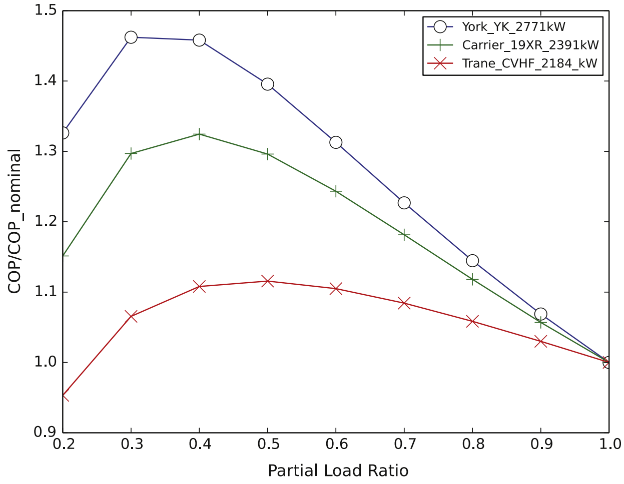

Fig. 2. The relationship between PLRs and the relative COPs for three different chillers calculated according to the chiller dataset provided by EnergyPlus [47].

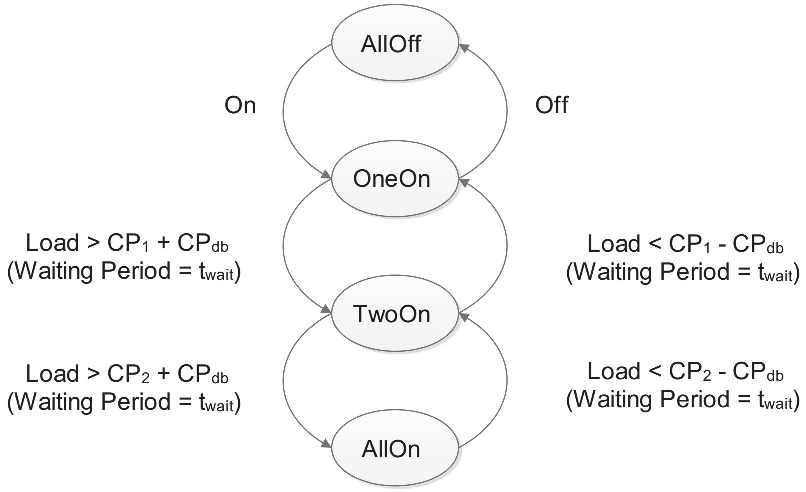

Fig. 1. The state machine of a conventional CLC for a chiller plant with three identical chillers.