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Development and validation of an effective and robust chiller sequence control strategy using data-driven models

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A B S T R A C T

Chiller sequence control significantly affects the efficiency and operation stability of plants with multiple chillers. However, in real practice, the energy efficiency is commonly sacrificed to avoid uncertainties. Also, the strategies found in literature may be too complicated to be used practically. An effective and robust strategy for centrifugal chiller plants is therefore developed. The strategy innovatively utilizes chillers inlet guide vane openings as the load, and more particularly the energy efficiency indicator. A validation of the use of such an indicator is conducted using the in situ measurements from the chiller plant in a high-rise building. The strategy is compared with two other commonly used strategies through tests. In the ideal condition (no measurement errors), the proposed strategy saves 3% of the energy comparing to the original strategy. When systematic errors exist in the cooling load measurements, energy performance of the plant is not affected when controlled by the proposed strategy.

1. Introduction

1.1. Background

As the largest energy consumers in central air-conditioning systems, chillers consume about 40% of the energy consumed by air-conditioning systems, and there is a strong potential to reduce the energy consumption of air-conditioning systems by enhancing the efficiency of chillers [1].

Optimal chiller sequence control, also known as optimal chiller loading, plays an important role in enhancing the chiller efficiency. In a well-designed large central air-conditioning system, multiple chillers are commonly used to fulfill the cooling load demand. The control of these chillers becomes important as they affect the cooling supply and the overall efficiency of chillers.

If the chillers are not well sequenced, they may either operate at low efficiency or fail to fulfill the demanded cooling load. In practical operations, chillers usually operate with low coefficients of performance (COP) due to the use of over-conservative control strategies. Those strategies force extra chillers to operate, resulting in a low partial load ratio (PLR) of all operating chillers. They also increase the operation time of water pumps, which further increases the energy consumption of the chiller plants.

Various advanced strategies are developed by researchers to solve the problem. For instance, data fusion technology [2] is used for chiller sequence control, which is validated using online data [3]. This technology takes the advantages of two cooling load calculation methods. Although the two methods suffer from measurement noises or model/systematic errors, the fused cooling load could have better accuracy [2]. Other available strategies include particle swarm optimization [4], Lagrangian method [5], genetic algorithm [6], differential evolution algorithm [7], and stochastic control method [8].

However, these technologies involve complicated operations and large storage capacity and cannot be implemented easily in common building management systems (BMS). BMS engineers and operators also find them to be difficult to understand because they are less logically deductive than the control strategies in practice and are uncertain of their reliability. Consequently, these complicated control strategies are not widely implemented in real air-conditioning systems.

To address these issues, the fault tolerant control method can be used [9]. In this paper, a chiller sequence control method that is tolerant to sensor errors is developed based on typical strategies using basic principles.

1.2. Typical chiller sequence control strategies

Different methods need different measurements to control chillers. Typical measurements used for chiller sequence controls are marked in Fig. 1.

1.2.1. Chilled water temperature based sequence control

The method determines chiller ON/OFF based on the return chilled water temperature [10,11]. If the return chilled water temperature is

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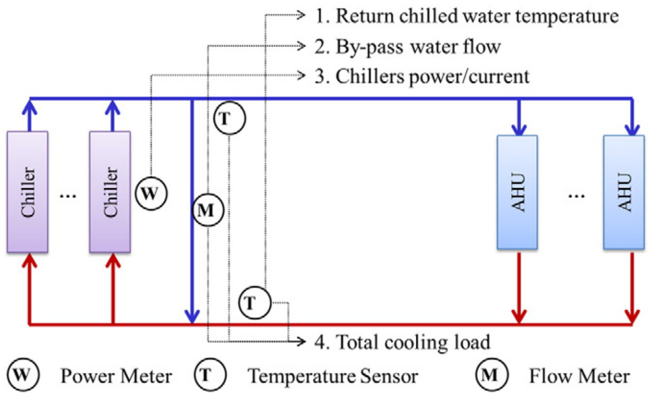

Fig. 1. Parameters required by different types of chiller sequence control strategies.

higher than a predefined maximum, an idling chiller will be staged on. If it becomes lower than a predefined minimum, a running chiller will be staged off. This method highly relies on the control of secondary chilled water pumps to ensure that the return chilled water temperature is a good indicator of the cooling demand. However, this method is neither precise nor reliable due to its complexity in practice.

1.2.2. Bypass water flow based sequence control

This strategy utilizes the water flow and the flow direction in the bypass line [10,11]. If the bypass water flow exceeds the design flow of a chiller plant, a running chiller will be staged off. If the flow is reversed, an idling chiller will be staged on. This strategy is also not precise or reliable in practice because the bypass water flow also depends on proper control of secondary chilled water pumps.

1.2.3. Chillers current or power based sequence control [10]

Chillers' current or power consumption can be a reliable indicator of chiller cooling load. This strategy stages on an extra chiller if its current or power consumption is near their rated values, and it stages off a running chiller if its current or power consumption is low. This method is not accurate because chiller COP and cooling capacity vary significantly with its operating conditions.

1.2.4. Total cooling load based sequence control

This strategy determines the number of operating chillers by comparing the maximum capacity of chillers with the cooling load [10]. It estimates the chiller cooling load by the chilled water flow and the difference between supply and return chilled water temperatures as demonstrated in Eq. (1). Although this strategy is considered as the best strategy in principle [10], its precision is vulnerable to measurement errors and uncertainties [3,10].

$$Q = c_p \cdot M_w \cdot (T_{ev,in} - T_{ev,out}) \tag{1}$$

where Q is the cooling load, c_p is the water specific heat, M_w is chilled water flow, and $T_{ev,in}$ and $T_{ev,out}$ are return (evaporator inlet) and supply (evaporator outlet) chilled water temperatures, respectively.

1.3. The proposed strategy and its innovation

This paper proposes an effective and robust chiller sequence control strategy to overcome the limitations of current control methods. The strategy eliminates the effects of the measurement errors on the control decisions and provides a method simpler to execute than the strategies in literature. This is mainly achieved by its use of inlet guide vane as a main and reliable indicator of the chiller efficiency. Although it is normally available in centralized multiple centrifugal chiller plants, its use in chiller sequence control is rare in both literature and practice.

The rest of the paper is organized in 6 sections. Section 2 presents the proposed effective and robust chiller sequence control strategy. Section 3 provides an in situ validation of the reliability of using chiller vane opening as chiller efficiency and load indicator. Section 4 describes the building and its air-conditioning system used for test and validation, the test platform built for evaluating the studied strategies, as well as the two reference strategies used for comparison. Section 5 presents the performance and limitations of a reference strategy in real application. The validation of the test platform is also conducted using in situ chiller operation data. Section 6 illustrates the comparison and discussion on the online test results, followed by the conclusion section.

2. The proposed effective and robust chiller sequence control strategy

Fig. 2 describes the logic of the proposed control strategy developed for a chiller plant in a high-rise building. Whether to stage on a chiller depends on the electric currents of operating chillers, vane openings, and supply chilled water temperatures. Specifically, a chiller is about to be staged on when the currents of all operating chillers have been near the full load current for a certain time threshold. This avoids frequent chiller on–off actions. The full load conditions of the operating chillers are further confirmed by monitoring their vane openings. By monitoring the temperature of supply chilled water to all individual zones, the strategy guarantees a sufficient cooling supply. If the chillers cannot satisfy the cooling demand, the supply chilled water temperature will be higher than its set point.

Whether to stage off a chiller is determined based on the chiller vane opening and the measured cooling load. The logic for staging off a chiller is activated only when one of the operating chillers has its vane opening less than 60%. This saves computational resources and may avoid staging off chillers unnecessarily. The control strategy then predicts the maximum cooling capacity of the chillers with one less operating chiller by a data-driven model in Eq. (2). Eq. (2) uses the multi-linear regression method [12], which is a type of machine learning algorithm, due to its simplicity and effectiveness. This model uses the evaporating and condensing pressures to predict the maximum cooling capacity and is trained using chiller full load operation data with a vane opening higher than 90%. Noticeably, even for identical chillers, they may have different coefficients in their corresponding models.

$$Q_{max,i} \sim lm(p_{ev,i}, p_{cd,i}) \tag{2}$$

where $Q_{max,i}$ is predicted maximum cooling capacity of the ith chiller, $p_{ev,i}$ and $p_{cd,i}$ are the evaporating and condensing pressure of the ith chiller, respectively, and $lm(\cdot)$ represents the multi-linear regression model.

3. Chiller vane opening *vs* energy efficiency and load—an in situ validation

This section presents the evaluation on the key parameters that are used as simple and reliable chiller efficiency indicators based on analyzing in situ operation data. Two parameters (i.e., PLR and chiller vane opening) are assessed.

3.1. Partial load ratio

PLR is defined as the ratio of the actual refrigeration (or cooling) load of a chiller to its full load capacity. It is well understood that high overall COP can be achieved by controlling a chiller to operate at its optimum PLR as they have strong correlation. Fig. 3 demonstrates such correlation between these two variables of a chiller in the studied building by using in situ operation data and manufacturer's catalog data obtained from test according to the ARI standard 550/590-1998 [13]. The COP of real operation data is lower than that in manufacturer's catalog due to