Energy and Buildings 84 (2014) 203–213

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Stochastic chiller sequencing control

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ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form 17 March 2014
Accepted 29 July 2014
Available online 7 August 2014

Keywords:
Chiller sequencing
Stochastic control
Cooling load measurement
Uncertainty
Multiple-chiller plant

ABSTRACT

Chiller sequencing control is essentially to determine proper thresholds for switching on and off chillers so as to guarantee that the operating chillers can provide sufficient cooling capacity while not waste energy for a given load condition. Total cooling load-based chiller sequencing control determines the thresholds according to building instantaneous cooling load and chiller maximum cooling capacity, which is in principle the best approach for chiller sequence control. However, one challenge for practical applications is that the measure of the cooling load and the estimate of the chiller maximum cooling capacity are associated with uncertainties. To deal with the uncertainties, a stochastic chiller sequencing control is proposed in this paper, which shows that the uncertainties associated with the cooling load measurement can be well described using Normal distribution and the uncertainties associated with the chiller maximum capacity estimation can be described using Uniform distribution. The switch-on/off thresholds are therefore determined in the framework of statistics. An algorithm to realize the stochastic control is developed. Case studies compare the stochastic control with the conventional deterministic method, and the results show that the proposed method can improve the robustness and flexibility of chiller sequencing operation.

1. Introduction

In modern complex buildings with large cooling load, a chiller plant is deployed to provide cooling to assure a comfortable indoor working environment. Due to its significant portion of the total building energy consumption, a proper control and maintenance of the chiller plant is of crucial importance to save the energy and/or operation cost of air-conditioning systems [1].

Among many control functions required during the chiller plant daily operation, chiller sequencing is a control function that determines how many and which chillers should be staged on or off for a given load condition. Essentially, chiller sequencing control should provide enough cooling capacity to satisfy the cooling demand from buildings while not waste energy [2–4]. Immoderate chillers that are staged on will certainly satisfy the cooling demand but will consume extra electrical energy. However, insufficient operating chillers cannot provide enough cooling capacity, and the indoor thermal comfort will be jeopardized consequently.

There are various methods of chiller sequencing control being used in different buildings including chilled water return temperature-based sequencing control, bypass flow-based sequencing control, direct power-based sequencing control, and total cooling load-based sequencing control [5,6]. All of those methods switch on or off a chiller according to the measurement of building instantaneous cooling load, but different methods use different ways of measurement. Basically, current available methods can be categories into direct and indirect methods. While direct methods determine the cooling load directly by measuring the total chilled water flow rate and the difference between the chilled water supply and return temperature, indirect methods determine whether the supplied cooling is sufficient or not based on certain 'indirect' indicators. For example, the 'bypass flow-based' method estimates the sufficiency of the provided cooling according to the direction and flow rate of the chilled water in the decoupled pipe; the 'power consumption-based' method estimates the sufficiency of the provided cooling according to the power consumption of the compressor in the chiller; and the 'temperature based' method estimates the sufficiency of the provided cooling only according to chilled water return temperature.

As those indirect indicators of cooling load may not be proportional to the cooling load, the direct method is more principally sound. There are two important variables in this control strategy.

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http://dx.doi.org/10.1016/j.enbuild.2014.07.072
0378-7788/

One is building instantaneous cooling load and the other is chiller maximum cooling capacity, both of which are used to determine switch-on and off thresholds [7].

On the cooling load measurement, due to small difference of the chilled water return and supply temperature, the noise in the temperature measurement could easily cause the measured value to deviate significantly from the actual value. A site survey conducted in 2001 shows that the inaccuracy of measured temperature difference can be as high as 30% [8]. That is the main reason why very few chiller plants adopt this type of control except for an application in a high-rise building in Hong Kong reported by Sun et al. [9]. To address the measurement uncertainty problems, Sun et al. [7] applied a virtual temperature sensor derived from a simplified chiller model to correct the bias of the real sensor; and Huang et al. [10] proposed to fuse the measurement from different sources to remove outliers and reduce biases.

It is known that individual chiller maximum cooling capacity varies with operating conditions, but the rated cooling capacity (usually provided by manufactures) is conventionally used as the maximum value. The difference between the real maximum capacity and the rated capacity will certainly affect the performance of chiller staging operations and energy consumption of the chilling plant as well. Several model-based methods were developed to estimate the maximum cooling capacity. For example, Jiang [11] and Jiang et al. [12] used an iteration loop to estimate chiller maximum cooling capacity that includes an energy balance of the cooling plant, chiller model and cooling tower model; Sun et al. [7] developed a simplified chiller model to calculate the maximum cooling capacity without any iteration loop. In these methods, uncertainties exist in the real-time estimation due to model uncertainties that cannot be avoided in many applications [13].

Different from previous studies of the total cooling load-based sequencing control, which are mainly focusing on uncertainty reduction but still use deterministic values for the cooling load and the chiller maximum cooling capacity, this paper proposes a stochastic sequencing control to determine the on/off stage of chillers. Stochastic sequencing control aims to improve the robustness of chiller sequencing operation by taking account of uncertainties directly in the decision making in the statistics framework [14–16]. Stochastic properties of the measured cooling load and the estimated cooling capacity will be studied, and a way of sequencing control will be developed according their stochastic properties. This paper will show that stochastic control can introduce flexibility in decision making and improve the robustness of sequencing operation; and will also show that the conventional deterministic chiller sequencing control strategy is actually a particular case in this statistics framework.

The rest of this paper is organized as follows. Section 2 introduces the principle of the cooling load-based chiller sequencing control and the ways of uncertainty description. Section 3 describes the basic idea of the proposed stochastic control and details of the control algorithm. Important application issues are also addressed in this section. Section 4 presents case studies that are used to evaluate the performance of the proposed control strategy. Finally, conclusion remarks are given in Section 5.

2. Total cooling load-based chiller sequencing control: uncertainties and stochastic modeling

2.1. Total cooling load-based chiller sequencing control

A multiple-chiller plant is shown in Fig. 1. Each chiller is coupled with a constant-flow pump, and the bypass pipe is used to balance the chilled water flow rate of the primary and secondary loop [2,4]. When the total cooling load-based chiller sequencing control is implemented, the thresholds of switching on or off a chiller is determined according to the basic requirements that (i) the provided maximum cooling should be larger than current load demand; and (ii) the overall power consumption of chillers should be or closed to the minimum.

The principle of the total cooling load-based chiller sequencing control is shown in Fig. 2. Assume there are z operating chillers with a total maximum cooling capacity C_{act}^z at the decision time, the $(z+1)$th chiller should be switched on for a given cooling load Q_{act} if

$$Q_{act} > H_{act,on}^z = \lambda^z C_{act}^z + \Delta \tag{1}$$

where

$$C_{act}^z = \sum_{i=1}^{z} C_{act,i}$$

The zth chiller should be switched off if

$$Q_{act} < H_{act,off}^z = \lambda^{z-1} C_{act}^{z-1} - \Delta \tag{2}$$

In Eqs. (1) and (2), Δ is a relay constraint that is used to avoid frequent switch-on and off of a chiller when the load is oscillating around the threshold (for chillers safety operation); and λ^z is a user-defined positive parameter, smaller than 1. The selection of λ^z depends on the performance curves of chillers (as also shown in Fig. 2), which is important for energy efficiency but will not be discussed in this paper. Interested reader may refer to ASHRAE Handbook 2011 [4].

In real situation, it is impossible to exactly know the actual cooling load Q_{act} and the maximum cooling capacity C_{act}^z. Hence, a measured cooling load Q_{mea} and an estimated maximum cooling capacity C_{cal}^z will be used instead in the decision making, *i.e.* at the decision time if $Q_{mea} > \lambda^z C_{cal}^z + \Delta$, then the $(z+1)$th chiller is switched on; if $Q_{mea} < \lambda^{z-1} C_{cal}^{z-1} - \Delta$, then the zth chiller is switched off; otherwise the current operating chillers will be maintained.

2.2. Cooling load measurement: uncertainty and stochastic modeling

To measure the cooling load, two temperature sensors and one water flow meter will be installed on the head pipes to measure the temperatures of return and supply chilled water and chilled water flow rate. The locations of the three measurement devices are shown in Fig. 1. Based on those measurements, the total cooling load for the chiller plant is calculated by

$$Q_{mea} = c_w \dot{m}_w (T_{rtn} - T_{\mathrm{sup}}) \tag{3}$$

where c_w is the specific thermal capacity of water; $\dot{m}_w$ is the water mass flow rate; and T_{rtn}, T_{sup} are chilled return and supply water temperature respectively.

Previous studies have shown that in real applications the measured cooling load Q_{mea} is not reliable due to noises in measuring the water temperature and the water flow rate [3,8,10], which may cause Q_{mea} to significantly deviate from its actual value. Measurement noise always follows a Normal distribution with zero expectation, *i.e.* being white noise [17]. Therefore, the noises e_{rtn}, e_{sup}, e_w are assumed to follow a Normal distribution. By taking account of measurement noises, the measured chilled water return temperature T_{rtn}, the supply temperature T_{sup} and the flow rate $\dot{m}_w$ are written as

$$\begin{aligned} T_{rtn} &= T_{rtn,act} + e_{rtn}, \quad e_{rtn} \sim N(0, \sigma_{rtn}) \\ T_{\mathrm{sup}} &= T_{\mathrm{sup},act} + e_{\mathrm{sup}}, \quad e_{\mathrm{sup}} \sim N(0, \sigma_{\mathrm{sup}}) \\ \dot{m}_w &= \dot{m}_{w,act} + e_w, \quad e_w \sim N(0, \sigma_w) \end{aligned} \tag{4}$$