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Uncertainty analysis for chiller sequencing control

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ABSTRACT

Chiller sequencing control is an essential function for a multiple-chiller plant that switches on and off chillers in terms of building instantaneous cooing load. It significantly affects both indoor temperature control (hence indoor thermal comfort) and building energy consumption. Various chiller sequencing controls have been developed and implemented in practice, and all of them switch on or off chillers according to a direct or an indirect indicator of the building instantaneous cooling load. Potential uncertainties in the direct or indirect indicator may cause the sequencing control misbehave and deteriorate the control and energy performance of the chiller plant. Until now, there is no any systematic study to investigate those uncertainties. This paper, therefore, proposes such a study. Four typical chiller sequencing controls are considered, including total cooling load-based sequencing control, return water temperature-based sequencing control, bypass flow-based sequencing control, and direct power-based sequencing control. Their uncertainty sources are identified and grouped into different categorizes. In order to facilitate the uncertainty modelling and analysis, all of those uncertainties are shifted to the load indicator of the corresponding sequencing control. Case studies are presented to show that using the proposed method of uncertainty shift and modelling the impacts of the uncertainties on the sequencing controls can be easily identified and analysed.

1. Introduction

A centralized chilling plant has been widely used in commercial buildings to provide cooling for indoor space. Normally, multiple chillers are used since this configuration is able to increase the operation flexibility of the chiller plant at different load conditions and therefore avoid the case that the online chillers have extremely low cooling load and improve the overall energy efficiency [1,2]. For a multiple-chiller plant, chiller sequencing control is an essential function. This control is used to switch chillers on or off according to current load condition, aiming at achieving an overall coefficient of performance (COP) of the online chillers as high as possible while fulfilling the demanded cooling load [3,4]. As the chilling plant is the key component in an air-conditioning system to provide cooling, proper behaviour of chiller sequencing control becomes significant for the energy and control performance of the air-conditioning system.

Various chiller sequencing controls have been developed and implemented in centralized chilling plants [5,6]. Different control may be suitable for different connection and configuration of chiller plants. Typical control strategies include the chilled return water temperature-based (T-based) sequencing control, the bypass flow-based (F-based) sequencing control, the direct power-based (P-based) sequencing control, and the total cooling load-based (Q-based) sequencing control. In practice, some applications combine these methods. For example, the chiller plant in the International Commerce Center (ICC) controls the chiller sequence by combining the P-based and Q-based strategies [7]; while the chiller sequence studied in [8] combines the P-based and F-based strategies. Although different controls have different switch-on and -off criteria, all of those criteria are essentially designed according to *a direct or an indirect indicator of building instantaneous cooling load* [9]. For example, the P-based method uses the percentage of full-load amperage (PFLA) of the compressor motors of the chill plant as an indicator of the building instantaneous cooling load; while the T-based control uses the chilled water return temperature as the indicator. To guarantee a precise and reliable control, all of the indicators should provide accurate reference information on building instantaneous cooling load. However, this is not always true in real applications due to the complexity of practical operating situation [9]. Uncertainty exists in these strategies.

Uncertainty is widely existent in engineering processes, such as in process modelling, control and management [10–12]. In heating, ventilation and air-conditioning (HVAC) systems, uncertainty

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and its importance have gradually been realized by researchers and engineers [12–17]. For example, Massoumy et al. proposed a method to handle model uncertainty in the control of HVAC processes [13]; Hopfe investigated uncertainties in building performance simulation and addressed the integration of a decision making protocol and optimization with the extension of uncertainty and sensitivity analysis [16]; Heo et al. studied how to incorporate additional uncertainties associated with retrofit technologies to generate probabilistic predictions of energy savings which can be naturally translated to risks associated with the investment [17]. In this study, uncertainty in the chiller sequencing control is studied, and it refer to a state that the cooling load indicator used in a particular sequencing control might not truly reflect the actual load condition. Although recent studies showed that uncertainty may have a significant impact on the chiller sequencing control [3,18], there is lack of a symmetrical study.

This paper, therefore, proposes a study on uncertainty analysis for chiller sequencing control. Uncertainty analysis, which aims to make a technical contribution to decision-making through the quantification of uncertainties in the relevant variables, has recently been introduced in HVAC engineering as an efficient tool to analyse the influence of uncertainties. For example, it was used to analyse the uncertainties in building energy simulation [19–21] and the uncertainties in heat transfer calculation [22,23]. In order to carry out the analysis, four typical chiller sequencing controls are taken into account, including total cooling load-based sequencing control, return water temperature-based sequencing control, bypass flow-based sequencing control, and direct power-based sequencing control. Their potential uncertainty sources are identified and grouped into different categorizes. To analyse the impacts of those uncertainties, uncertainty should be modelled and integrated into HVAC software, such as TRNSYS, for simulation study. However, those uncertainties are not easy to simulate due to their complexity. Hence, a method of uncertainty shift is developed in this paper. All of those uncertainties are shifted to the load indicator of the corresponding sequencing control and then only the uncertainties associated with the indicator should be considered when studying the impacts of all of those potential uncertainties. The impacts of the uncertainties are evaluated using three performance indices: the total chiller switch number, the energy use of the chiller plant, and the accumulated tracking error of the supply air temperature (SAT). The latter is considered because the SAT accumulated tracking error may affect the indoor temperature control and hence the indoor thermal comfort.

2. Typical chiller sequencing controls

2.1. Decoupled multiple-chiller plant

A typical decoupled multiple-chiller plant is divided into two loops by a bypass line (titled as decoupler): the primary chilled-water production loop and the secondary chilled-water distribution loop. As illustrated in Fig. 1, multiple chillers are connected in parallel in the primary loop. Each chiller is interlocked with a constant-speed pump. Normally the set point for the chilled water supply (CHWS) temperature is set as the same for all the online chillers. The chilled supply water from different chillers is mixed in the header supply pipe, flowing to the secondary loop or back to the chillers (through the bypass line) depends on the load condition. In the secondary loop, the chilled water is distributed by multiple variable speed pumps to air-handling units (AHUs) to cool down the supply air that is delivered to the space where cooling is required. The chilled water flow rate and the speed of the pumps are controlled by the differential pressure measured at the most remote (critical) operating AHU.

The principle of chiller sequencing control is shown in Fig. 2, where the x-axis is the building instantaneous cooling load, which is calculated by

$$Q = c_w \dot{m}_p \left(T_{\text{rtn}} - T_{\text{sup}} \right) \quad (1)$$

where c_w is the chilled water specific heat capacity (kJ/kg °C); $\dot{m}_p$ is the chilled water mass flow rate in primary loop header pipe (kg/s); T_{rtn} is the chilled water return (CHWR) temperature (°C) and T_{sup} is the CHWS temperature (°C). The ideal thresholds, denoted by Q_z^{th} and Q_{z+1}^{th}, are the intersection points of the total power curves of online chillers. When the load is smaller than the threshold Q_{z+1}^{th}, the use of z chillers is better than $z+1$ chillers in terms of energy efficiency. Since not all of central chilling plants provide the measure of building instantaneous cooling load, various types of chiller sequencing control have been developed and typical ones include [9]:

- Total cooling load-based (Q-based) sequencing control.
- Return water temperature-based (T-based) sequencing control.
- Direct power-based (P-based) sequencing control.
- Bypass flow-based (F-based) sequencing control.

2.2. Total cooling load-based (Q-based) sequencing control

The Q-based control calculates the building instantaneous cooling load by Eq. (1). The calculated (or measured) cooling load is compared with the thresholds (see Fig. 2) to determine the operation of chiller sequence. Generally, a dead band is adopted in this control to make the switch-on threshold Q_z^{on} (from z to $z+1$) slightly larger than the corresponding switch-off threshold Q_z^{off} (from $z+1$ to z), as shown by the following equations:

$$Q_z^{\text{on}} = \eta \times Q_r (z + d) \quad (2)$$

$$Q_z^{\text{off}} = \eta \times Q_r (z - d) \quad (3)$$

where d, a percentage, is a user-defined dead band; Q_r is the chiller rated cooling capacity (here it is assumed that each chiller has the same rated cooling capacity). The use of the dead band can avoid frequent switch actions when the load is at the boundary [7]. Considering potential measurement noises or other disturbances, a period of continuous measurement is normally used as time limit [5,8]. Hence, the switch-on/off criteria are:

- *Stage-on criterion:* IF the measured cooling load is larger than a predefined threshold and this state lasts for a period longer than the time limit, THEN a chiller and its interlocked pump will be switched on.
- *Stage-off criterion:* IF the measured cooling load is smaller than a predefined threshold and this state lasts for a period longer than the time limit, THEN a chiller and its interlocked pump will be switched off.

2.3. Return water temperature-based (T-based) sequencing control

The T-based control switches chillers on or off according to the CHWR temperature only. This control assumes that (i) the CHWS temperature is fixed as a constant; and (ii) when the number of online chillers is fixed, the water mass flow rate in the primary loop is constant. In this case, the building instantaneous cooling load is affine to the CHWR temperature, see Eq. (1). Hence, the thresholds for chiller switch-on/off can be defined according to the CHWR temperature and the number of online chillers. The switch-on/off criteria of the T-based control are: