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Robustness analysis of chiller sequencing control

Yundan Liao [a], Yongjun Sun [b], Gongsheng Huang [a,*]

[a] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong
[b] Division of Building Science and Technology, City University of Hong Kong, Hong Kong

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ABSTRACT

Multiple-chiller plant is commonly employed in the heating, ventilating and air-conditioning system to increase operational feasibility and energy-efficiency under part load condition. In a multiple-chiller plant, chiller sequencing control plays a key role in achieving overall energy efficiency while not sacrifices the cooling sufficiency for indoor thermal comfort. Various sequencing control strategies have been developed and implemented in practice. Based on the observation that (*i*) uncertainty, which cannot be avoided in chiller sequencing control, has a significant impact on the control performance and may cause the control fail to achieve the expected control and/or energy performance; and (ii) in current literature few studies have systematically addressed this issue, this paper therefore presents a study on robustness analysis of chiller sequencing control in order to understand the robustness of various chiller sequencing control strategies under different types of uncertainty. Based on the robustness analysis, a simple and applicable method is developed to select the most robust control strategy for a given chiller plant in the presence of uncertainties, which will be verified using case studies.

1. Introduction

A chiller plant is a key component of a central air-conditioning system, providing cooling for indoor space so as to achieve indoor thermal comfort [1]. Chiller plant represents the largest primary energy end-use in a central air-conditioning system. In typical commercial buildings, chiller plant accounts for 10–20% of the overall facilities usage [2]. In the subtropical area like Hong Kong, this percentage climbs to about 40% of the total annual electricity expenditure [3]. In order to improve operational feasibility and energy efficiency under part load condition, a chiller plant is always configured with multiple chillers connected in parallel [4]. In this configuration, chiller sequencing control is an essential function that switches chillers on or off according to building instantaneous cooling load, aiming at achieving an overall coefficient of performance (COP) of the online chillers as high as possible while fulfilling the demanded cooling load [5].

Various chiller sequencing control strategies have been developed and implemented in chiller plants, using a direct or an indirect indicator of building instantaneous cooling load [6]. Typical control strategies include chilled water return temperature-based (T-based) sequencing control, bypass flow-based (F-based) sequencing control, direct power-based (P-based) sequencing control, and total cooling load-based (Q-based) sequencing control. These control strategies are widely applied in practice and their performance has significant impacts on system energy efficiency, system stability and indoor thermal comfort [7].

To guarantee a precise and reliable chiller sequencing control, uncertainty impacts cannot be neglected and need to be well considered [8]. Uncertainty refers to a state of having limited knowledge where it is impossible to exactly describe the existing state [9]. Uncertainties have been considered in the operation of chiller plants. For example, Jiang et al. [10,11] studied the uncertainties in model-based optimization of chiller plants; Huang et al. [12] investigated the measurement uncertainties in the total cooling load-based control; and Li et al. [13] developed a stochastic chiller sequencing control to deal with the measurement uncertainties in the Q-based chiller sequencing control. These studies indicate that due to the existent of uncertainties, current control is not as reliable as expected, which may explain why a large number of commercial buildings do not use automated chiller sequencing control and prefer to switch on/off chillers experimentally and manually [10].

In order to develop a more robust control strategy, a systematical study to analyze the impacts of uncertainties on chiller sequencing control becomes necessary. Such as study was presented by Liao et al. [14]. Their study showed that the performance of those typical sequencing control strategies was significantly

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* Corresponding author. Tel.: +852 34422408; fax: +852 34420427.
E-mail address: gongsheng.huang@cityu.edu.hk (G. Huang).

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Nomenclature

A	amplitude
COP	coefficient of performance
c_w	chilled water specific heat capacity (kJ/kg °C)
D	combined index
E_n	energy use (kW h)
ΔE_n	variation of energy use
I	electrical current of compressor (A)
$\dot{m}$	flow rate of chilled water (kg/s)
n_c	number of components
N_t	switch number
ΔN_t	variation of total switch number
PF	power factor
$PFLA$	percentage of full load amperage
PLR	part load ratio
P_{UC}	under-cooling percentage
ΔP_{UC}	variation of under-cooling percentage
Q	cooling load (kW)
Q_c	chiller rated capacity (kW)
T	temperature (°C)
w	weighting factor
Δt	time step

Superscript

on	switch on

Subscripts

b	bypass
con	control uncertainty
i	ith term
k	sampling time
m	flow rate
max	maximum
$meas$	measured
$oper$	operation uncertainty
p	primary loop
r	rated
rtn	return chilled water
s	secondary loop
st	set-point
sup	supply chilled water
t	total
z	zth threshold
0	without uncertainty

Greek Symbols

ε	user-defined parameter (°C)
δ	accuracy of sensor
Δ	uncertainty
σ	standard deviation
ξ_k	Boolean variable
τ	total operation time period (min)
ω	frequency (Hz)

deteriorated by uncertainties. However, the severity of uncertainty impacts may depend heavily on the amplitude and/or frequency spectrum of uncertainties, and it is still unclear how robust those typical chiller sequencing controls will be when they are subject to different levels of uncertainties.

This paper, therefore, presents a systematic robustness analysis of chiller sequencing control in order to understand the robustness of those typical chiller sequencing control strategies to different uncertainties. In order to analyze the robustness of those typical sequencing control strategies, potential uncertainties are modeled and propagated using a detailed simulation platform with a Monte-Carlo method [15], which is a sample-based method that is commonly adopted to analyze the stochastic properties of uncertainties [16]. The performance variation of those typical sequencing control strategies are compared in terms of chiller total switch number, under-cooling percentage and energy use.

Robustness analysis identifies the level of sensitivity of a chiller sequencing control strategy to different uncertainties that it might suffer from [17]. It will be used to provide suggestions for chiller plant operators to analyze the performance of their chiller plants and find ways of improving the performance. As various uncertainties may exist and impact the performance simultaneously, robustness analysis based on a detailed simulation is complex and may be time-consuming for practical applications. Hence a simple numerical method is also developed in this study, which provides much convenience in selecting proper chiller sequencing control by conducting robustness analysis without using a detailed simulation platform.

The purposes of this paper are to investigate the robustness of those typical chiller sequencing control strategies when they are subject to different uncertainties and to develop a simple numerical method to select the most robust sequencing control for a given chiller plant by taking account of uncertainties. The rest of the paper is organized as follows. Section 2 describes the principle of chiller sequencing control and uncertainties associated with those typical control strategies. Section 3 introduces the methodology of the robustness analysis, and presents the results and analysis as the methodology is implemented in a decoupled multiple-chiller plant. Section 4 develops the simple numerical method and case studies are conducted to verify its effectiveness. Finally, the conclusion remarks are given in Section 5.

2. Chiller sequencing control and uncertainties

2.1. Chiller sequencing control

The principle of chiller sequencing control is shown in Fig. 1, where the x-axis is the building instantaneous cooling load, calculated by Eq. (1)

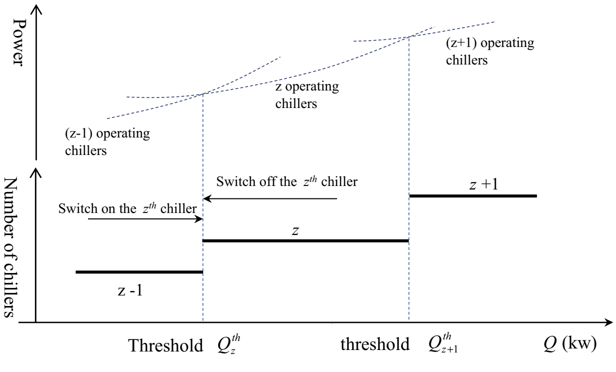

Fig. 1. Basic principle of chiller sequencing control.