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Research Paper

Robustness enhancement for chiller sequencing control under uncertainty

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HIGHLIGHTS

- Methods to enhance the robustness of chiller sequencing control were developed.
- The proposed methods hybridizes the use of different load indicators.
- The proposed methods were evaluated under different levels of uncertainty.
- The proposed methods show their robustness even when the uncertainty is significant.

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ABSTRACT

Chiller sequencing control is an important technique for achieving energy efficiency of multi-chiller plants while not sacrificing indoor thermal comfort. Available typical controls, such as bypass flow-based control and direct power-based (P-based) control, uses individual indicator to switch chillers on or off. However, these controls suffer from various uncertainties in operation and may lead to insufficient cooling supply, unstable operation, or energy waste. A simple but practical way to enhance the robustness of chiller sequencing control is to explore and make use of the complementarity of different load indicators. Hence, this paper presents three methods to enhance the robustness of chiller sequencing control by hybridizing the use of different load indicators. Numerical studies are used to analyze the robustness of the enhanced controls under different levels of uncertainty.

1. Introduction

Centralized air-conditioning (AC) systems are widely used in modern buildings to provide thermal comfort and healthy indoor environment [1–3]. Multiple-chiller plant, as the major component in a central AC system, consumes > 60% of the total energy use of the AC system [4–6]. To guarantee a central AC system working in an energy efficiency manner, chiller sequencing control is always adopted in multiple-chiller plants [7–10]. Chiller sequencing control determines when and which chiller should be switched on or off for a given cooling load condition [11]. Essentially, it is used to keep chiller plants working with a high coefficient of performance (COP) while at the same time be able to satisfy the cooling demand of buildings [12,13]. As shown in [14], it can save the energy by 14% when properly used; however, it may cause the supply air temperature fluctuating and deteriorate indoor thermal comfort when not properly used as reported by [15].

In current practice, four typical sequencing controls are used, including *total cooling load based (Q-based) control, chilled water return temperature based (T-based) control, direct power based (P-based) control and bypass flow rate based (F-based) control* [16]. Previous studies have shown that these controls suffer from different uncertainties in their operation, which may cause the control performance deviate from expectation. For instance, the uncertainty in measuring cooling load resulted in delayed or earlier chiller on/off action in the Q-based control [17]. This misbehavior increased unnecessary switching action by 50% and cooling capacity unmet hour by 53% [18]. Therefore, it becomes necessary to enhance the robustness of chiller sequencing control.

Robustness is a property of controller, which describes its capability to tolerate the effect of uncertainty or variation in system parameters [19]. To enhance the robustness of chiller sequencing control many studies have been carried out [11,20–25]. Huang et al. [11] proposed a data fusion technique to reduce the measurement uncertainty in the estimation of building cooling load. Li et al. [13] applied stochastic theory to model the cooling load measurement and the maximum chiller cooling capacity to determine the switch action. Johnson control [20] developed a sequencing control using a chiller efficiency trapezoid model to reduce the impact of measurement errors. Shan et al. [21] developed a data-driven model to deal with sensor errors. However,

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Nomenclature

COP	coefficient of performance
COP_r	rated coefficient of performance
Δ_{COP}	COP error
c	number of components
C_w	chilled water specific heat capacity (kJ/kg·°C)
d	dead band
E_n	energy use (kWh)
ΔE_n	variation of energy use (%)
$E_{n,0}$	energy use of benchmark case (kWh)
$PleaseCheck$	bypass flow rate (L/s)
$\dot{m}_w$	primary chilled water flow rate (L/s)
n_c	number of components
N_t	switch number
ΔN_t	variation of total switch number (%)
$N_{t,0}$	total switch number of benchmark case
P_{meas}	measured power (kW)
P_{UC}	under-cooling percentage (%)
ΔP_{UC}	variation of under-cooling percentage (%)
P_{zth}^{on}	switch-on threshold of P-based control (kW)
P_{zth}^{off}	switch-off threshold of P-based control (kW)
$P_{zth,sub}^{on}$	threshold of subsidiary criterion (kW)
PLR	part load ratio
PLR_{zth}	part load ratio related to the zth threshold
Q	cooling load (kW)
Q_{zth}^{on}	switch-on threshold of Q-based control (kW)
Q_{zth}^{off}	switch-off threshold of Q-based control (kW)
T_{rtn}	CHWR temperature (K)
T_{rup}	CHWS temperature (K)
$T_{rtn,meas}$	measured CHWR temperature (K)
$T_{sup,meas}$	measured CHWS temperature (K)
$T_{sup,st}$	setpoint of CHWS temperature (K)
$\Delta T_{sup,db}$	dead band of CHWS temperature (K)
$\Delta_{\mathrm{con,oper}}$	control/operational uncertainty
T_{zth}^{on}	switch-on threshold of T-based control (kW)
T_{zth}^{off}	switch-off threshold of T-based control (kW)
t	simulation time (min)
Δt	sampling time step
t_{on}	switch-on time limit
t_{off}	switch-off time limit
α	dead-band for bounding COP dots
ε	user-defined parameter (°C)
ξ_k	Boolean variable
σ	standard deviation
μ	expected value
ω	frequency (Hz)
τ	total operation time period (min)

these technologies involve complicated operations and models, which may not be easy for practical applications. Straightforward but simple controls, like those four typical controls, are still preferable in practice.

Liao et al. [25,26] found that current typical controls uses individual load indicator but have somehow complementary regarding to uncertainties. For instance, the P-based control has a reliable load indicator since the electrical power can be measured accurately and reliably, but it may have long time delay in switching actions due to a threshold uncertainty [25]. In contrast, the T-based control and the F-based control have a less reliable load indicator but do not suffer from the threshold uncertainty. It is possible to enhance their robustness by utilizing the complementary advantages in different load indicators. Therefore, in this work, three methods are proposed to enhance the robustness of chiller sequencing control by hybridizing the use of different load indicators. Case studies will be carried out to show the effectiveness of the proposed strategies.

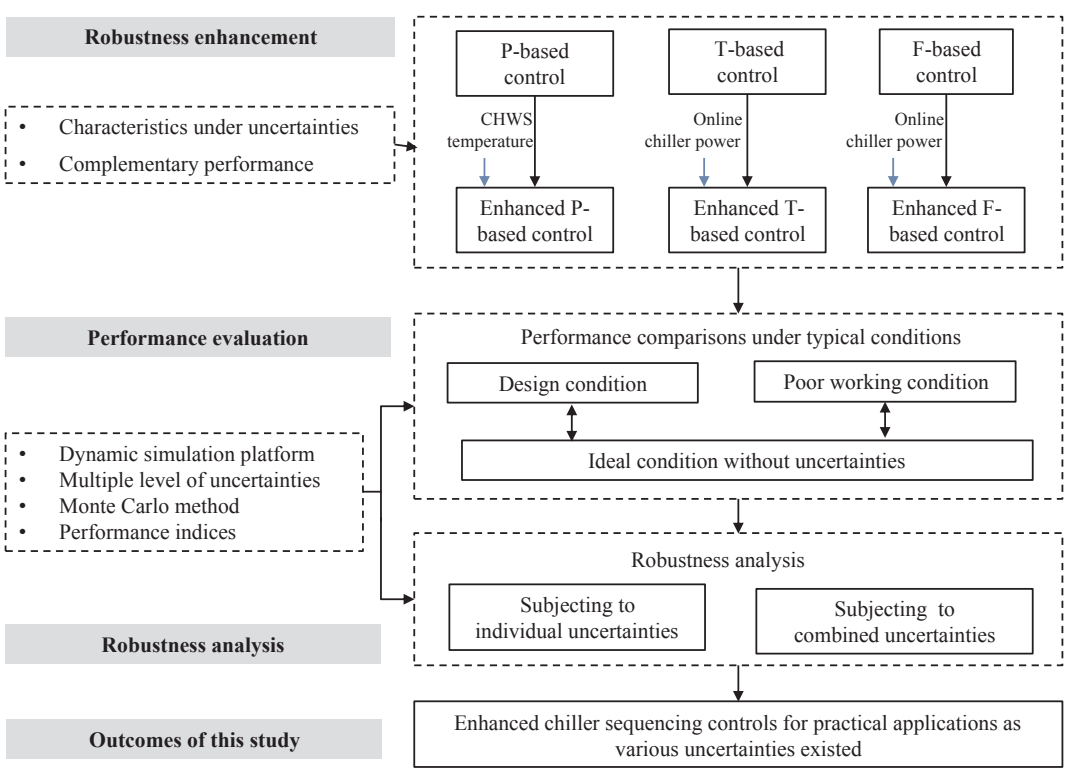

Fig. 1. Methodology of developing hybrid strategy for chiller sequencing control.

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