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Diversity of energy-saving control strategy for a parallel chilled water pump based on variable differential pressure control in an air-conditioning system

Liu Xuefeng*, Liu Jinping, Lu Zhitao, Xing Kongzu, Mai Yuebang

School of Electric Power, South China University of Technology, Guangdong Provincial Academy of Building Research, Wushan RD., Tianhe District, Guangzhou 510641, PR China

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ABSTRACT

An analytical model of a parallel chilled water pump set was established in this study. The bypass-loop adjustment characteristic was found to be a key component of this model. A pump set consisting of four of the same type of pumps was the focus of this study, and the running characteristics for five types of control strategies were examined in detail: the control strategy of the power frequency pump quantity control, the hybrid control strategy of a single pump of variable frequency combined with power frequency pump quantity control, the control strategy of two pumps of synchronous variable frequencies, the control strategy of three pumps with synchronous variable frequencies, and the control strategy of four pumps with synchronous variable frequencies. These strategies were analyzed under different supply–return water differential pressures. It was proposed that the hybrid control strategy of single pump variable frequency combined with power frequency pump quantity control is most suitable for variable flow to the chilled water system under a low flow ratio or a high supply-return water differential pressure.

1. Introduction

The energy consumption of chiller systems accounts for a major portion of electricity consumption in commercial buildings.

The parallel form of multiple chilled water pumps is the typical structure of a central air-conditioning system, and variable flow operation is the most popular energy-saving means of implementing a chilled water system. With the same pipe network flow, the energy consumption of a parallel pump set depends on its control strategy. Liu et al. [1] studied the bypass loop and the characteristics of pump energy consumption under many different supply-return water differential pressures for a chilled water pipe network. When the speed of a variable frequency pump was reduced, the motor efficiency and frequency converter efficiency sharply declined to varying degrees, and variable frequency operation alone could not completely replace the bypass control valve. The extreme value analysis method is an online optimization allocation method for determining the operating conditions of a parallel variable frequency pump [2]. Gao et al. [3] studied the primary pump system of an air-conditioning system in detail, and indicated that the more similar the hydraulic characteristics of the air-conditioning terminal device and the chilled water pipe network are, the better the operational efficiency of the variable frequency pump becomes; in addition, the energy-saving rate can exceed 10%. Furthermore, the operation frequency of a chilled water pump was optimized, and the optimal flow and energy consumption of the chilled water system were analyzed through global optimization. The differential pressure of the most unfavorable loop is used to replace the supply-return water differential pressure of the main pipeline as the feedback control signal, which is the most common variable pressure difference control method for a pump set; this approach is also the simplest and feasible method for the energy-saving operation of a pump set [4–6]. Taking into account the effect of the supply-return water differential pressure on the operational characteristics of a pump set for a chilled water pipe network, Ma et al. [7] discussed the energy consumption characteristics of pump set with a differential pressure controller being installed in the balance pipe of the secondary pump system, and found that the installed differential pressure controller can save more energy. However, Zhao et al. [8] and Yang

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* Corresponding author. Tel.: +86 13580456068.
E-mail address: lyxfliu@scut.edu.cn (L. Xuefeng).

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Nomenclature

Δp_{branch}	effective pump heads of the chilled water pump set (Pa)
Δp_{head_pump}	pump heads (Pa)
Δp_{branch_tube}	on-way frictional resistance of the pump set branch line (Pa)
Δp_{branch_local}	local frictional resistance of the pump set branch line (Pa)
S_{branch_tube}	connecting tube impedance of the pump set branch line (Pa·s^2/kg^2)
S_{branch_local}	local impedance of the pump set branch line (Pa·^{2}/kg^2)
G	chilled water flow of the pump set branch line (m^3/h)
$S_{chiller}$	chiller impedance
$S_{chillers}$	total impedance of the chillers (Pa·s^2/kg^2)
$S_{chiller\_branch\_n}$	pipeline impedance of the chiller branch (Pa·s^2/kg^2)
$S_{chiller\_branch\_tube}$	connecting tube impedance of the chiller branch (Pa·s^2/kg^2)
$S_{chiller\_branch\_local}$	local impedance of the chiller branch (Pa·s^2/kg^2)
$\Delta p_{chillers}$	differential pressure of the parallel pipe network of chillers (Pa)
H_{head}	pump heads (Pa)
P_{pump_motor}	pump motor power (kW)
η_{pump}	pump efficiency
η_{motor}	pump motor efficiency
$\eta_{converter}$	pump frequency conversion efficiency
H_n	pump heads with *n* frequency (m)
A, B, C, D, E	constant associated with the pump
A', B', C', D', E'	constant associated with the pump
η_n	pump efficiency with *n* frequency
Δp_{branch}	effective head of the chilled water pump set (Pa)
G_{actual}	actual flow of the bypass control valve (m^3/h)
G_{max}	max flow of the bypass control valve under certain pressure condition (m^3/h$_{)}$
Δp_{valve_set}	differential pressure set value of the bypass loop (Pa)
S_{valve_min}	minimum impedance of the bypass control valve (Pa·s^2/kg^2)
K	bypass control valve opening (%)
Δp_{bypass_actual}	actual differential pressure of the bypass loop (Pa)
$H_{head\_availabe}$	effective pump head of the chilled water pump set (m)
G_{user_side}	user-side flow of the chilled water pipe network (m^3/h)
G_{bypass}	bypass flow of the chilled water pipe network (m^3/h)
S_{bypass_min}	minimum impedance of the bypass loop (Pa·s^2/kg^2)
λ	on-way resistance coefficient
ξ	local resistance coefficient
$G_{user\_side\_rated}$	chilled water rated flow of the user-side pipe network (m^3/h)
L_{bypass}	length of the bypass pipeline (m)
Δ_{bypass}	roughness of the bypass pipeline (m)
ξ_{bypass}	local resistance coefficient of the bypass pipeline (kg/s)
$D_{cold-source}$	main pipeline diameter of the cold source side (m)
$L_{cold-source}$	main pipeline length of the cold source side (m)
D_{branch}	branch pipeline diameter of the pump set (m)
L_{branch}	branch pipeline length of the pump set (m)
ξ_{branch}	local resistance coefficient of the branch pipeline of pump set
$\xi_{chiller\_branch}$	local resistance coefficient of the branch pipeline of chiller
$\Delta_{cold-source}$	roughness of the cold source side pipe network (m)
D_{bypass_valve}	pipeline diameter of the differential pressure control valve (m)
$\xi_{cold-source}$	local resistance coefficient of the cold source side main pipe (m)
$G_{single\_pump\_rated}$	rated power of a single pump (m^3/s)

et al. [9] have ignored the regulatory role of the bypass loop and considered the characteristic curve of a chilled water pipe network to be approximately constant, simplified model was beneficial in engineering applications, but this assumption is only suitable for low flow ratios and synchronously frequency, these researchers' findings were subject to some limitations, which can't resolve hydraulic imbalance problems under the conditions of asynchronous frequency regulation for pumps set network, if you ignore the water resistance of pump connecting pipe, optimal control strategy may need to be amended. Syed et al. [10] discussed the energy consumption of different pump schemes, including the single loop variable primary pump scheme, the constant primary pump and variable secondary pump scheme and the single loop constant pumping scheme, and proposed that by replacing the existing single loop constant pump scheme with a constant primary pump and variable secondary pump scheme, an 8% savings in total annual energy consumption can be achieved, which can be increased to 13% by adopting a single loop variable primary pump scheme. Similarly, an approximately 7% reduction in annual energy consumption is obtained by adopting the constant primary pump and variable secondary pump scheme under the climatic conditions of Riyadh and Jeddah. However, if the single loop variable pump scheme is adopted, the energy savings for Riyadh and Jeddah will increase to 12% and 11%, respectively, and only a single pump is considered in which the operating characteristics of the pump set is ignored. The use of multivariate and data envelopment analyses to facilitate the energy management of chiller systems was found to be an effective method. Yu et al. [11] thank that a system containing three sets of chillers, pumps and cooling waters that serves as an institutional building was used to validate these analyses. Envelopment analysis was then conducted to calculate the scale, technical and overall efficiencies of the proposed model; however, the analytical model ignored the intrinsic physical mechanism of the chilled water pipe network. The variable frequency operation of a pump set is often less effective than the ideal energy-saving approach implemented in practical engineering applications, and the root cause is the fact that the essential characteristics of a chilled water system are ignored; in particular, the adjustment characteristics of the bypass loop are overlooked. When an air-conditioning system cooling load appears step changes, pump operating frequency under constant temperature control mode may increase or decrease, which is a key element for control quality. For example, if temperature difference control object value remains at 7 °C, the pump frequency reduces from 35.5 Hz to 26 Hz when flow ratio increases from 60% to 70%, and regulating process may affect air-conditioning comfortableness. If the temperature difference control object value is controlled at 5 °C, the water pump frequency increases from 36.5 Hz to 38 Hz, and regulating process does not affect air-conditioning comfortableness. Therefore, a reasonable control target of temperature difference can achieve good control quality, which depend on the adjustment characteristics of the bypass loop [12,13]. In this study, the hydraulic