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A new hydraulic regulation method on district heating system with distributed variable-speed pumps

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ABSTRACT

Compared with the hydraulic configuration based on the conventional central circulating pump, a district heating system with distributed variable-speed-pumps configuration can often save 30–50% power consumption on circulating pumps with frequency inverters. However, the hydraulic regulations on distributed variable-speed-pumps configuration could be more complicated than ever while all distributed pumps need to be adjusted to their designated flow rates. Especially in a multi-source looped structure heating network where the distributed pumps have strongly coupled and severe non-linear hydraulic connections with each other, it would be rather difficult to maintain the hydraulic balance during the regulations. In this paper, with the help of the advanced automation and information technologies, a new hydraulic regulation method was proposed to achieve on-site hydraulic balance for the district heating systems with distributed variable-speed-pumps configuration. The proposed method was comprised of a new hydraulic model, which was developed to adapt the distributed variable-speed-pumps configuration, and a calibration model with genetic algorithm. By carrying out the proposed method step by step, the flow rates of all distributed pumps can be progressively adjusted to their designated values. A hypothetic district heating system with 2 heat sources and 10 substations was taken as a case study to illustrate the feasibility of the proposed method. Two scenarios were investigated respectively. In Scenario I, the flow rate of one substation varied according to its heat demand and the flow rates of other substations maintained their original values. And in Scenario II, the flow rates of all substations varied synchronously with the same relative rate. The results of the both scenarios indicated that all pumps could be properly adjusted to their designated flow rates by the proposed method with a high frequency adjustment resolution as 0.001 Hz. In scenario I, compared with the district heating system with distributed variable-speed-pumps configuration, the power consumption would be 26.6–66.8% less than that of the conventional central circulating pump configuration during the 4 rounds of regulations. In scenario II, the energy saving ratio of the district system with distributed variable-speed-pumps configuration would be 36.1–90.3% less than that of the conventional central circulating pump configuration during the 5 rounds of regulations.

1. Introduction

In the building sector, 46% of the total worldwide energy demand can be attributed to heating and cooling [1]. In China, as He et al. investigated, the building sector represented more than 30% of the total energy consumption in 2014 [2]. In order to relief environmental impact, many countries and area have taken various actions to encourage more energy savings in building sector [3]. In China, it was found by Chen et al. that the energy saving and emission reduction have gotten more attention in recent years [4]. Jiang et al. presented the necessity of developing low-carbon economy, clean energy including the new energy and the renewable energy in China [5]. And Cai et al. indicated that the building energy consumption had been regarded as a crucial problem of the current society [6].

District heating (DH) has shown to be a promising technology to address sustainability in building-related energy production and distribution. Möller et al. described a geographical study of the potential to expand district heating into areas supplied with natural gas [7]. Ancona et al. concluded that the district heating allows achieving high conversion efficiencies by centralizing in few large power plants the need of thermal energy in household sector [8]. To enhance energy efficiency and environmental sustainability, a

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Nomenclature

A	associated matrix of pipe network
B	basic circuit matrix of pipe network
d	diameter of pipe (m)
e_{tol}	allowable difference ratio of the flow rate (%)
E_p, ΔE_p	power consumption (W)
f	friction factor
Fr	frequency (Hz)
g	gravity acceleration (m/s^2)
$\Delta H, \Delta H_p$	head of pump (Pa)
k_0, k_1, k_2	fitting coefficient
L	length of the pipe (m)
n	rotation speed (rpm)
P	pressure (Pa)
Δp	differential pressure (Pa)
Q	volume flow rate (m^3/h)
r_0, r_1, r_2	fitting coefficient
ΔR, R	hydraulic resistance (Pa)
R_p	resistance of each branch (Pa)
Re	Reynolds number

Greek symbols

ρ	density (kg/m^3)
ε	roughness of inner surface of pipe (m)
η_{Pump}	efficiency of pump (%)
ψ_p	relative energy saving ratio (%)

Superscripts

d	designated value
e	estimated value
f	feed water or supply water
r	return water
$rate$	rated value
u	measured value

Subscripts

i	index of a pump
k	index of a pipe branch
m	index of a substation
s	index of a source

Abbreviations

CCCP	conventional central circulating pump
CHP	combined heat and power plant
CS	cloud service
DH	district heating
DHS	district heating system
DVSP	distributed variable speed pump
GIS	geographical information system
RC	remote control (system)
SCADA	supervisory control and data acquisition (system)

variety of new heat sources are accessed to the DH systems. Especially, many renewable energies and industry surplus heats can be utilized as heat sources available to DH systems. For instance, Lund et al. [9] defined a scenario framework in which the Danish system would be converted to 100% renewable energy sources in the year 2060. Li et al. studied a district heating case applied industrial surplus heat of steel plants in North China [10]. Olsthoorn et al. presented that the heat storages and renewable energy could also be integrated into DH to promote energy efficiency [11].

Many countries have already been benefited from a rapid growth with of the advanced DH systems such as China, Denmark, Sweden, Austria, and many other European countries. The economic analysis presented by Wang et al. showed the superiority of the building substation system with annual cost reductions ranging between 5.7 and 5.9% for a lifetime range of 10–30 years [12]. Münster et al. showed that district heating may contribute to the sustainability and security of supply of future energy systems in Denmark [13]. Brange et al. showed that the potential for excess heat prosumers would be fairly big, in Hyllie, Sweden, around 50–120% of the annual heat demand [14]. Köfinger et al. [15] showed that lower heat losses due to lower network temperatures would be beneficiary for the low temperature district heating network performance in rural areas. Persson et al. studied 83 cities in Belgium, Germany, France, and the Netherlands, and the results showed that the average heat market share for district heat within these cities was 21% during 2006 [16]. Nowadays, some large DH systems have gradually developed to a meshed network with multiple sources, substations and end users (buildings). For instance, Vesterlund et al. studied the methods for simulation [17] and optimization [18] of a complex meshed network in the town of Kiruna (Sweden), which has been developing since the 1960s. There have been many large-scale DH systems in the cities in North China, as Xu et al. investigated, where almost 74% of the DH systems are comprised of the primary and secondary networks instead of direct connection to the service buildings [19].

The modern large scale DH systems are managed towards smart thermal grids in the near future. In 2014, Lund et al. [20] proposed the 4th Generation District Heating for future sustainable energy systems. In the 4th generation DH, smart thermal systems will need advanced technology improvements to support the efficient and sustainable development in the configuration, design and operation. Brand et al. [21] investigated how low the DH supply temperature can be without reducing the current high level of thermal comfort for occupants or the good efficiency of the DH network. It was indicated in this research that renewable sources of heat can be integrated into the DH system without problems as low as 60 °C. Laajalehtoa et al. [22] introduced a ring topology design and a mass flow control method to improve the energy efficiency of low temperature district heating. The results were shown that energy losses, including heat losses, pumping energy could be reduced by the proposed method.

Distributed variable-speed pumps (DVSPs) configuration has been one of the most important improvements for the DH development. Compared with the hydraulic configuration based on the conventional central circulating pump (CCCP) method, a DH system with DVSPs configuration can often save as much as 30–50% power consumption on water circulation. Shi estimated that a number of DH systems with DVSPs configuration have provided space heating and domestic hot water to over 10 million m^2 construction areas in China [23]. The energy saving ratio is as much as 50% or even more in some newly built or retrofitted DH systems with DVSPs configuration compared to those with CCCP configuration [23]. Yan et al. [24] compared the hydraulic performance between the DH system with DVSPs configuration and the same DH system with CCCP configuration in Kuerle, China. Two operation cases of DH were investigated in the paper, including (I) the flow rate varies in all of the loops simultaneously, and (II) the flow rate varies only in one of the loops. The simulation results of the two cases indicated that the power consumption of the DVSPs system was 71% and 31% less than that of the CCCP system respec-