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Hydraulic performance optimization of meshed district heating network with multiple heat sources

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ABSTRACT

Operational optimization is the key to energy reduction of the district heating (DH) system. Poor hydraulic performances of the DH network will largely increase the energy consumption. However, for most meshed DH networks with multiple heat sources, the optimal hydraulic conditions are usually not achieved. In this paper, the hydraulic performance optimization problem of meshed DH network with multiple heat sources was proposed. In order to solve the problem, the General Reduced Gradient (GRG) algorithm was adopted to minimize the total pump power through optimizing the pump frequencies and substation valve openings of the DH network. The hydraulic performances of the GRG algorithm based optimal control (OC) strategy were compared with the traditional constant pressure difference control (CPDC) and the constant speed control (CSC) strategies. Results shows that in comparison with the CPDC and CSC strategy, the total pump power can be reduced by 20% and 65% respectively, when applying the OC strategy. And the hydraulic intersection point of the DH network was changeable to reallocate the serving areas of heat sources and optimize the total pump power. Besides, increasing the pump efficiency without considering the hydraulic constraints of the DH network may not lead to optimal conditions.

1. Introduction

With the environmental and energy issues becoming the central problems of social development, techniques of energy efficient utilization are paid more attentions. As an indispensable infrastructure of the modern urban facilities, the district heating (DH) system has been globally used for many years for its high efficiency, safety and economics. DH systems cover more than 50% of the heat supply. Besides, there is a large potential in integrating the renewable thermal energy into the DH network. The renewable heat sources such as solar thermal energy [1] and industrial waste heat [2–4] could be connected to the district heating network, which leads to the concept of the next generation, more energy-efficient and environmentally-friendly DH systems [5]. The integration of renewable thermal energy can largely improve the energy efficiencies and environmental effects of DH systems, which will greatly contribute to the sustainability of the energy industries. The integration of renewables to the DH network will increase the complexity of the network topology. Therefore, techniques on the operational optimization of the DH networks are imperative, especially for large-scale, complex-topology, meshed DH networks with multiple heat sources.

Predictive control strategy is one of the most effective approaches to resolve the optimal supply temperature control problem of the DH systems, in which thermal dynamic involves. Predictive control strategy calculates a time series of the future supply temperature set-points at each time instant, which minimizes the objective of energy cost. Sandou et al. [6] proposed a predictive control strategy of the district heating networks, which computed an optimal and robust control actions to optimally operate the supply temperature of the heat source. László and János [7] proposed a tuning method for the nonlinear predictive controller, which was developed for the DH network to fulfill the control goal. Steer et al. [8] studied the frequency of adjustments to the supply temperature set-point in predictive control of the DH networks, which influences the overall operating cost in two ways: adaptability to changes in network conditions and availability of time for determining an appropriate response. Although the predictive control strategy can deal with thermal dynamic

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Nomenclature

a, b, c	The parameters of pump head curve
α, β, γ	The parameters of pump efficiency curve
b_{ij}	The (i,j) element of basic incidence matrix B_k
B_k	The basic incidence matrix of DH network
$B_{k,rm}$, $B_{k,sb}$, $B_{k,sc-1}$, $B_{k,t-1}$, $b_{t,sc}$	Submatrices of the basic incidence matrix of DH network
c_{ij}	The (i,j) element of independent loop matrix C_f
C_f	The independent loop matrix of DH network
$C_{f,rm}$, $C_{f,sb}$, $C_{f,sc-1}$, $C_{f,t-1}$, $c_{t,sc}$	Submatrices of the independent loop matrix of DH network
d	Direction vector in GRG algorithm
E_{t-1}	Index set of tree branches excluding the heat source tree branch
E_{sc}	Index set of heat source branches
E_{sb}	Index set of heating substation branches
E_{rm}	Index set of residual branches in the meshes
f_j	Pump frequency of the j th heat source (Hz)
f_o	The power frequency, $f_o = 50$ Hz in China
F, H	Matrices to calculate the general reduced gradient
G_R	The general reduced gradient of total pump power
I	Identity matrix
k	Iteration step number
$K_{v,i}$	Valve flow capacity of the i th heating substation
m	Number of nodes minus one
N_i	The i th node on supply pipelines
N_i'	The i th node on return pipelines
n	Number of branches
n_{dl}	Number of independent loops in the DH network
n_{ms}	Number of meshes in the DH network
n_{rm}	Number of residual branches in the meshes
n_{sc}	Number of heat sources
n_t	Number of tree branches
O	Zero matrix
Δp_j	The j th element of pressure drop vector ΔP (Pa)
ΔP	Pressure drop vector of all the branches of the DH network (Pa)
q_j	The j th element of flow rate vector Q (t/h)
q_{pipe}	The flow rate of the pipeline (t/h)
Q	Flow rate vector of all the branches of the DH network (t/h)
Q_{t-1}	Flow rate vector of tree branches excluding the heat source tree branch (t/h)
Q_{sc-1}	Flow rate vector of heat sources excluding the heat source tree branch (t/h)
Q_{sb}	Flow rate vector of heating substation (t/h)
$Q_{sb,req}$	Flow rate requirement of heating substations (t/h)
r	Pump frequency ratio
R_i	Control valve controllable ratio of the i th heating substation
s	Hydraulic resistance (Pa/(t/h)^2)
s_{pipe}	The hydraulic resistance of pipeline (Pa/(t/h)^2)
W_{Total}	Total pump power of DH network
x	Valve opening
η_j	Pump efficiency of j th heat source
ε	Specified small value to scale the step length
ε	Specified small value for the convergence condition

characteristics of the DH networks, the online optimization calculation of the predictive control actions will be slow and difficult for the complex topological DH networks, due to the nonlinearities of thermal and hydraulic coupling. Hence, the predictive control strategy has only been applied to small scale DH network with simple topology.

The steady state approaches for thermal characteristic modeling and operational optimization of the DH networks attracted numerous attentions, due to the tractability and effectiveness of the steady state solution of temperature distribution along the pipeline. With the steady state modeling approach, Li et al. [9] proposed an integrated multi-scale modeling method to simulate the operation performance of combined heat and power based district heating system, including the heat loss, pressure drop, pump power and supply temperatures. In the study of Wang et al. [10], a mathematical model describing the steady-state thermal conditions of the DH systems and a model parameter calibration method were proposed. Due to the nonlinearities of the DH system operation optimization problem, nonlinear optimization methods or global optimization approaches such as GA (Genetic Algorithm), GSO (Group Search Optimizer) etc. are suitable. Jie et al. [11] utilized the MATLAB software to calculate the optimization problem of reducing pumping and heat loss cost to determine the heating parameters. Jiang et al. [12] proposed a GSO based optimal operating strategy of an integrated energy based direct district water-heating system, to minimize the fossil fuel consumption of the system in daily operation by calculating the optimal set-point temperature of boilers and water flow rate of pump. Fang and Risto [13] developed a GA based method for optimizing the heat production simultaneously at multiple heat plants at different locations of a DH network to minimize the combined production and distribution costs. Although these studies considered the pumping energy, the hydraulic performance of the DH network, which is the key to distribution efficiency of the DH system, is not concerned.

Variable speed pump DH systems can improve the hydraulic performances significantly and increase the distribution efficiency of the DH network [14]. Based on Kirchhoff's laws, Yan et al. [15] developed a hydraulic model and a parameter calibration method to simulate the hydraulic performance of a distributed variable speed pump DH system. In the study of Tatu et al. [16], the energy efficiency of a ring topology DH system with distributed pumps and mass flow control is examined by means of both technical and economic analysis. These studies considered the hydraulic performances of DH network, while the operation for large scale DH network with meshed topology and multiple heat sources was not discussed.

For large scale meshed DH network with multiple heat sources, hydraulic performances are usually not at the optimum conditions [17], which will lead to low efficiency and high pumping cost. To solve the problem, hydraulic performance simulation and operation strategy optimization for large scale meshed DH network with multiple heat sources are necessary. An efficient method for numerical simulation and analyses of the steady state hydraulics of complex pipeline networks based on network loop model and the square root method was developed [18]. A reduced model based on Proper Orthogonal Decomposition combined with Radial basis functions was proposed by Elisa et al. [19] to optimize the total pump power of large district heating network with multiple heat sources, which allowed maintaining high level of accuracy despite reductions of more than 80% of the computational time compared with the CFD method. Nevertheless, the variations of pump efficiencies at different operation conditions were not considered in