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Integrated heat and power dispatch truly utilizing thermal inertia of district heating network for wind power integration

Jinfu Zheng, Zhigang Zhou*, Jianing Zhao*, Jinda Wang

School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150090, China

HIGHLIGHTS

- Integration model is first proposed for dynamic temperature distribution of DHN.
- A new integrated heat and power dispatch for wind power integration is proposed.
- Integration model is embedded into the IHPD to truly use thermal inertia of DHN.
- Stored heat and heat storage rate of DHN are quantitatively calculated.
- Supply and return temperature at HS are optimised for operation regulation of DHS.

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ABSTRACT

Utilizing the thermal inertia of a district heating network (DHN) for thermal storage is considered an effective energy-saving method for improving the operational flexibility of combined heat and power (CHP) generation units for wind power integration in an integrated heat and power dispatch (IHPD) system. However, to truly utilize the thermal inertia of the DHN, the supply and return temperatures at the heat source are both necessary to regulate the district heating system (DHS) for wind power integration, whereas the heat output of CHP is not able to do that. Therefore, a new IHPD model that considers the thermal inertia of the DHN was formulated to improve the flexibility of CHP units for wind power integration, in which the first proposed integration model was used to completely simulate the dynamic temperature distribution of the DHS. The optimised supply and return temperatures at the heat source were then obtained to guide the operation regulation of DHS for wind power integration in actual engineering applications. Moreover, the stored thermal energy and the thermal storage rate of the DHN were quantitatively calculated to determine the thermal state of DHN. To analyse the effects of the proposed IHPD model, the approach was compared with a conventional heat and power dispatch model through a case study based on a real DHS. The results demonstrate the advantages of the proposed model in terms of wind power integration, energy saving and operation regulation of DHS.

1. Introduction

In recent years, the use of wind power has rapidly developed around the world in response to the challenges faced by a limited amount of fossil fuels and global environmental problems [1,2]. In China, the installed capacity of wind power reached 149 GW in 2016 [3], contributing to 34.7% of the wind power capacity globally [4].

However, the use of wind power is often restricted by the strong interdependence between electricity and thermal generation of the combined heat and power (CHP) generation units [5,6]. In Jilin Province in north-eastern China, over 70% of the heat loads are supplied using CHP units owing to their high energy efficiency [7], which generally operate in a heat-led mode to meet the heat demand in real time. During winter nights, with a high heat load but low power load, the heat output of the CHP increases significantly, as does the electricity output, which results in a significant curtailment of the wind power. According to statistics from the National Energy Administration of China, the quantity and rate of wind power curtailment were 49.7 TWh and 17.1% in 2016, respectively [3].

Hence, improving the operational flexibility of the CHP can significantly improve the use of wind power, such as installing electric heat boilers, heat pumps and heat storage tanks. Lund et al. presented an analysis of different methods for increasing the share of wind power in the Danish energy system through the use of heat pumps and heat

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* Corresponding authors at: Box 2651, 202 Haihe Road, Nangang District, Harbin Institute of Technology, Harbin, 150090, China (Z. Zhou). Box 2644, 73 Huanghe Road, Nangang District, Harbin Institute of Technology, Harbin, 150090, China (J. Zhao).

E-mail addresses: hit_zzg@163.com (Z. Zhou), zhaojn@hit.edu.cn (J. Zhao).

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Nomenclature

Parameters

A^i	area of buildings heat by heat exchanger i (m^2)
C^k	operation cost of kth corner point of CHP (¥)
$c_{p,f}$	specific heat of water (J/ (kg °C))
d	pipe diameter (m)
G_{chp}	mass flow rate of CHP (kg/s)
G^j	mass flow rate of pipe j (kg/s)
G^i	mass flow rate of heat exchanger i (kg/s)
K	overall heat transfer coefficient (W/(m °C))
K_{cpg}	unit-price of purchased power (¥/kWh)
N	number of corner points of CHP
$n,m,W\ X,Y,Z$	intermediate parameters of node method
(Q^k,P^k)	heat and electricity output of CHP corresponding to kth corner point (MW)
q_h	area heat index (W/(m^2 °C))
s	total scheduling period
$\underline{T}/\overline{T}$	min/max temperature in a DHN (°C)
T_n	design indoor temperature (°C)
U	number of heat exchanger
V	volume flow rate of pipe (m^3/s)
$\Delta\underline{P}/\Delta\overline{P}$	downward/upward ramping capability of CHP (MW/h)
$\Delta\tau$	time step interval (s)
δ	unit-penalty of wind power curtailment (¥/kWh)
ρ_f	density of water (kg/m^3)
$\mathbf{A}$	basic incidence matrix of DHN
$\mathbf{B}$	connection pipe matrix
$\mathbf{C}$	inlet node matrix
$\mathbf{D}$	connection pipe number matrix
$\mathbf{d}$	pipe diameter vector
$\mathbf{K}$	overall heat transfer coefficient vector
$\mathbf{n},\mathbf{m},\mathbf{W},\ \mathbf{X},\mathbf{Y},\mathbf{Z}$	intermediate matrixes of node method
$\mathbf{G}$	mass flow rate vector of pipe
$\mathbf{V}$	volume flow rate vector of pipe

Variables

C_{chp}	operation cost of CHP (¥)
C	daily operation cost of IHPD system (¥)
C_{cpg}	purchased power cost (¥)
C_w	penalty cost of wind power curtailment (¥)
P_{cpg}	purchased power from connected power grid (MW)
P_{aw}	available wind power (MW)
P_w	integrated wind power (MW)
P_{load}	electricity load (MW)
(Q_{chp},P_{chp})	heat and electricity output of CHP (MW)
Q^i	heat output of heat exchanger i (MW)
Q_{load}^i	heat load of buildings heat by heat exchanger i (MW)
Q_v	thermal storage rate of DHN (MW)
$Q_{chp,re}$	reference heat generation of CHP (MW)
Q_{load}	total heat load of DHS (MW)
T_s/T_r	supply/return temperature of CHP (°C)
T_{out}^j	outlet temperature of pipe j (°C)
T_{in}^k	inlet temperature of pipe k (°C)
T^i	temperature of node i (°C)
T'_{out}	preliminary outlet temperature of pipe (°C)
T_e	environment temperature (°C)
T^j/T^k	temperature of start/end connecting-nodes of heat exchanger i (°C)
α^k	combination coefficients of CHP
$\Delta Q_{\tau_1-\tau_2}$	stored thermal energy of DHN from time step τ_1 to time step τ_2 (MWh)
$\mathbf{E},\mathbf{F}$	temporary matrixes
$\mathbf{Q_{load}}$	heat load matrixes of heat exchanger
$\mathbf{T}$	node temperature matrix
$\mathbf{T_e}$	environment temperature vector

Superscripts

1	primary side of heat exchanger
2	secondary side of heat exchanger

Subscripts

τ	time step (s)

thermal storage [8]. Nielsen et al. investigated the economic value of heat pumps and electric boilers in the Danish energy system for wind power integration [9]. Papaefthymiou et al. studied the potential application of heat pumps for demand-side management and wind power integration in the German electricity market [10]. Chen et al. explored opportunities for increasing the flexibility of CHP units using electrical boilers and heat storage tanks for a better integration of wind power [11]. Zhang et al. proposed an improved unit-commitment-based power system using a chronological simulation to evaluate the potential benefits from pumped hydro storage and electric boilers for wind power integration in western Inner Mongolia [12]. Waite et al. analysed the potential for increased wind-generated electricity utilisation using heat pumps in New York city [13]. These measures indeed reduce the wind power curtailments as well as improve the operating efficiency; however, excessive equipment investment may preclude the employment of such measures.

Therefore, an increasing number of researchers have been paying attention to the utilisation of thermal inertia of the district heating network (DHN) and buildings for wind power integration. Pan et al. proposed a new feasible region-based method to model the flexibility of the district heating system (DHS), particularly considering the thermal inertia of buildings, in an integrated heat and electricity dispatch (IHPD) model [14]. Jiang et al. modelled an integrated energy-based direct water-heating system for operation optimisation, which also considers the thermal inertia of buildings [15]. However, in the literature [14,15], the dynamic temperature of the DHN was not taken into consideration, which has a significant impact on the DHS operation because the corresponding time delays are typically from a few minutes to several hours [16]. On the contrary, Li et al. proposed another IHPD model that considers the temperature dynamics of pipelines for exploiting the pipeline energy storage as an option for wind power integration [16]. In addition, Yang et al. took the temperature dynamics of pipelines, the thermal inertia of buildings, and the thermal comfort of end users into consideration to facilitate wind power integration in a wind-thermal power system [17]. Gu et al. proposed an optimal operation model for an integrated energy system combining the thermal inertia of the DHN and buildings to enhance the absorption of wind power, in which the temperature dynamics and transmission delay in the pipelines and the thermal storage capacity of the buildings were studied [18].

It should be noted that, although the studies in [16–18] state that the temperature dynamics of the DHN have been simulated, in reality only the pipe models were built by node method [19,20] or other simplified methods. Based on the pipe models and simple temperature transfer relationship between pipes (such as 'the pipe outlet temperature is equal to the inlet temperature of the subsequent pipe'), the