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Coordinated dispatch of multi-energy system with district heating network: Modeling and solution strategy

Shuai Lu [a], Wei Gu [a, *], Jinhui Zhou [b], Xuesong Zhang [b], Chenyu Wu [a]

[a] *School of Electrical Engineering, Southeast University, Nanjing, 210096, China*
[b] *Zhejiang Electric Power Corporation Research Institute, Hangzhou, 310014, China*

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ABSTRACT

This paper proposes a dispatch strategy for the multi-energy system (MES) that utilizes the district heating network (DHN) to realize the heat power interaction of multi cogeneration system, so as to improve the operational flexibility. A novel model for the DHN that couples multi heat sources and is under quantity regulation is proposed, based on which an optimal coordinated dispatch model (OCDM) for the MES is presented comprehensively. The DHN model comprises dispatch constraints (DCs) and linear system of temperature correction equations (TCEs). The DCs form part of the OCDM constraints, where the mass flow temperatures are treated as constants and the mass flow rates and heat power are decision variables. The TCEs are employed to update the mass flow temperatures in DCs. Subsequently, an iterative solving strategy for the OCDM is proposed. The convergence of the solving strategy is analyzed and an effective method is introduced to ensure the convergence. A modified system based on an actual MES in Changchun, China is researched in the case study. Three cases are given to verify the effectiveness of the dispatch strategy and the solution method as well as study the influence of wind power penetration and heating level to the results.

1. Introduction

With the depletion of traditional fossil fuels, people are devoted to developing and utilizing new renewable and environmental energy resources [1,2]. The multi-energy system (MES), which consists of cogeneration system, has high energy utilization rate, and provides efficient support for the local consumption of renewable energy sources, making it a promising solution to build a green and sustainable energy system [3–5]. In the MES, combined heating and power (CHP) or combined cooling, heating, and power (CCHP) system are main components that supply multi kinds of energy to meet demand [6–8]. District heating network (DHN) links energy system and load together in the MES by thermal energy and plays an important role in coordinating the supply and demand [9,10].

Many studies are focused on the modeling and algorithms of the MES dispatch. The work on modeling ranges from the basic principle of devices and entire systems to the operation in handling the actual dispatch problems such as operation strategies, uncertainties, and so on [11–13]. In Ref. [14], a multi-period generalized network flow model which incorporates the primary energy (including coal and natural gas) and electricity was proposed for the MES to evaluate the economic efficiency. In Ref. [15], the model predictive control was utilized to deal with the uncertainties of renewable energy sources and loads, and an online operation model including two hierarchies (rolling optimization and real-time feed correction) were proposed. A two-stage stochastic operation model considering electrical and thermal storage system was presented in Ref. [16] for the day-ahead dispatch of CHP system, where the first stage determines the operations parameters and the second stage deals with the stochastic contingency scenarios. The work on algorithms is inclined to solve nonlinear and nonconvex dispatch problem with different methods. In Ref. [17], a self-adoptive learning with time varying acceleration coefficient gravitational search algorithm was proposed to solve the highly nonlinear, nonconvex, and high-dimension energy hubs dispatch. In Ref. [18], a decentralized solution consisting of central heating system process and electrical power system process for the CHP dispatch was proposed, and an iterative solving strategy was constructed.

In most of the above studies, the heat load is often modeled as

* Corresponding author.
E-mail address: wgu@seu.edu.cn (W. Gu).

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Nomenclature

Sets

N	Set of indices of dispatch time.
$\Theta_{sr}/\Theta_{sb}/\Theta_{in}$	Set of indices of heat sources/heating substations/intersection points.
$\Gamma^i_{sr}/\Gamma^i_{sb}/\Gamma^i_{in}$	Set of indices of pipelines connected with heat source/heating substation/intersection point i.
Γ_p	Set of indices of pipelines.
Ω_{CHP}	Set of indices of CHP system.

Parameters of DHN

$\dot{m}^{i,t}$	Mass flow rate of pipeline i in interval t (kg/h).
$\dot{m}^{i,t}_+/\dot{m}^{i,t}_-$	Mass flow rate of pipeline i in interval t consistent with/opposite to the reference direction (kg/h).
$\underline{\dot{m}}^i/\overline{\dot{m}}^i$	Minimum/maximum mass flow rate of pipeline i (kg/h).
$\varepsilon^{i,t}_{pipe+}/\varepsilon^{i,t}_{pipe,-}$	State variables to determine the direction of the flow in pipeline i in interval t.
μ^i	Coefficient relating pressure drop to mass flow rate of pipeline i (m/kg).
$\Delta p^{i,t}$	Press loss of pipeline i in interval t (N).
ρ	Density of mass.
η_{pump}	Efficiency of pump.
c	Specific heat capacity of water (J/(kg·°C)).
$\tau^{i,t}_{S,head}/\tau^{i,t}_{S,tail}$	Mass flow temperature in the head/tail of supply pipeline i in interval t(°C).
$\tau^{i,t}_{R,head}/\tau^{i,t}_{R,tail}$	Mass flow temperature in the head/tail of return pipeline i in interval t (°C).
$\tau^{i,t}_{S,node}/\tau^{i,t}_{R,node}$	Mass flow temperature of the node i in supply/return pipelines in interval t (°C).
τ_S/τ_R	Designed supply/return temperature (°C).
$Q^{i,t}_{S,head}/Q^{i,t}_{S,tail}$	Heat power of the flow in the head/tail of supply pipeline i in interval t (kW).
$Q^{i,t}_{R,head}/Q^{i,t}_{R,tail}$	Heat power of the flow in the head/tail of return pipeline i in interval t (kW).
$Q^{i,t}_{sr}/Q^{i,t}_{sb}$	Output heat power of the heat source/heating substation node i in interval t (kW).
λ^i	Heat transfer coefficient of pipeline i (kW/(m·°C)).
l^i	Length of pipeline i (m).

Parameters of CHP system

Δt	Length of time interval (h).
f	Objective function of the dispatch model (¥).
C^i_{CHP}	Cost function of the CHP system i (¥).
C_{grid}	Cost of interacting with the grid (¥).
R_{ng}	Price of natural gas (¥/m^3).
H_{ng}	Heating value of natural gas (kW/m^3).
$R^t_{grid,b}/R^t_{grid,s}$	Price of electricity purchased from/sold to the grid in interval t (¥/kWh).
$P^t_{grid,b}/P^t_{grid,s}$	Power purchased from/sold to the grid in interval t (kW).
$\overline{P}_{grid}$	Maximum grid interacting power (kW).
$P^{i,t}_{CHP}$	Output electrical power of CHP system i in interval t(kW).
P^t_{load}	Electrical load of the district in interval t (kW).
P^t_{res}	Electrical power of renewable energy in the CHP system i in interval t (kW).
α^i_{gt}	Heat-electricity ratio of the gas turbine in the CHP system i.
η^i_{gt}	Electrical efficiency of the gas turbine in the CHP system i.
$P^{i,t}_{gt}/Q^{i,t}_{gt}$	Electrical/heating output power of gas turbine in the CHP system i in interval t (kW).
$\underline{P}^i_{gt}/\overline{P}^i_{gt}$	Minimum/Maximum electrical power of gas turbine in the CHP system i (kW).
$\varepsilon^{i,t}_{gt}$	State of gas turbine in the CHP system i in interval t.
$\eta^i_{gb}/\eta^i_{hr}/\eta^i_{he}$	Efficiency of the gas boiler/heat recovery unit/heat exchanger in the CHP system i.
$Q^{i,t}_{gb}/Q^{i,t}_{hr}/Q^{i,t}_{he}$	Heating output power of gas boiler/heat recovery unit/heat exchanger in the CHP system i in interval t (kW).
$\overline{Q}^i_{gb}/\overline{Q}^{i,t}_{hr}/\overline{Q}^{i,t}_{he}$	Maximum heating output power of gas boiler/heat recovery unit/heat exchanger in the CHP system i (kW).
$\sigma^i_{bt}/\sigma^i_{tst}$	Energy loss rate of battery/thermal storage tank in the CHP system i.
$\eta^i_{bt,chr}/\eta^i_{bt,dis}$	Charging/discharging efficiency of the battery in the CHP system i.
$P^{i,t}_{bt,chr}/P^{i,t}_{bt,dis}$	Charging/discharging power of the battery in the CHP system i in interval t (kW).
$W^{i,t}_{bt}/W^{i,t}_{tst}$	Energy level of the battery/thermal storage tank in the CHP system i in interval t (kW).
$\underline{W}^i_{bt}/\overline{W}^i_{bt}$	Lower and upper bound of the capacity of battery in the CHP system i (kWh).
$\eta^i_{tst,chr}/\eta^i_{tst,dis}$	Charging/discharging efficiency of thermal storage tank in the CHP system i.
$Q^{i,t}_{tst,chr}/Q^{i,t}_{tst,dis}$	Charging/discharging power of thermal storage tank in CHP system i in interval t (kW).
$\overline{Q}^{i,t}_{tst,chr}/\overline{Q}^{i,t}_{tst,dis}$	Maximum charging/discharging power of thermal storage tank in the CHP system i in interval t (kW).
$\underline{W}^i_{tst}/\overline{W}^i_{tst}$	Lower/upper bound of the capacity of thermal storage tank in the CHP system i (kWh).
$\varepsilon^{i,t}_{grid,s}/\varepsilon^{i,t}_{grid,b}$	State variables of selling/purchasing electricity of the CHP system i in interval t.
$\varepsilon^{i,t}_{bt,chr}/\varepsilon^{i,t}_{bt,dis}$	Charging/discharging state variables of the battery in the CHP system i in interval t.
$\varepsilon^{i,t}_{tst,chr}/\varepsilon^{i,t}_{tst,dis}$	Charging/discharging state variables of thermal storage tank in the CHP system i in interval t.

nodes and the transmission process of the thermal energy is always neglected. These simplifications are reasonable in small-scale scenarios where the thermal energy is transferred within a small range, such as building CHP/CCHP system and industrial area CHP/CCHP system [19–21]. However, in some large-scale scenarios such as residential MES, the heat load is decentralized and the transmission distance of thermal energy is long so that the influence of DHN must be considered, including the energy loss and transmission delay. Quality regulation (regulating the temperature of supply water) and quantity regulation (regulating the flow rates) are two main operation strategies in the DHN operation and different strategies lead to different model [22,23].

Although lots of researches are related to the planning and operation of DHN [24,25], only a few of them are focused on the dispatch of the multi-energy system (MES) and DHN. In Ref. [26], a detailed DHN model under quality regulation considering the