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Phase-change heat storage installation in combined heat and power plants for integration of renewable energy sources into power system

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ABSTRACT

Due to the nature of fluctuation and intermittence, integration of renewable energy sources (RESs) requests more flexibility of power systems. However, the "heat-led" operation mode limits the adjustability of combined heat and power (CHP) plants, and reduce the accommodation of RESs. This paper studies an integrated thermal and power system and introduces a phase-change heat storage (HS) facility into the CHP plant to improve the adjustability, where the heat released from the extraction steam is not consistent to the heat load at each moment. Furthermore, the heat transfer processes in the HS facility are modelled as a thermal resistance network, which provides the feasibility for analyzing the integrated system in a unified model. On this basis, the operation plan of the integrated system is optimized by the linear programming (LP) method to minimize the wind energy loss. The results show that: 1) HS facility installation increases the flexibility of power system, and reduces the wind energy loss from 18.7% to 11.2%. 2) Heat transfer processes should be carefully taken into account for precisely setting the power generations of each plant. 3) The phase-change temperatures of HS materials should be between 90 °C and 100 °C for the maximum wind power accommodation.

1. Introduction

Energy and environment have been attracting a high level of global attention for decades due to the huge consumption of fossil fuels [1,2], where improving energy utilization efficiency and replacing fossil energy sources are recognized as two effective solutions [3,4]. For improving utilization energy efficiency, combined heat and power (CHP) systems have been widely applied in industry, which use the heat that would be wasted in a conventional power plant to satisfy the heat load and potentially reaches an energy utilization efficiency of up to 80% [5]. For replacing fossil energy sources, the utilization of wind energy, solar energy, and other renewable energy sources (RESs) has been rapidly developed in these years. It not only reduces the usage of fossil fuel, but also provides better environmental benefits [6–9].

Due to fluctuation and intermittence, the utilization of RESs requires more flexibility of power system [10–12]. However, the existing CHP systems are commonly operated in the "heat-led" mode, which limits the regulation range of heat-to-electric ratio and then reduces the adjustability of CHP systems. Even worse, because the installed capacity of CHP systems becomes larger nowadays, the flexibility of power system is further limited, and a large amount of renewable energy is abandoned.

One of the efficient ways to improve the flexibility of power system is to improve the flexibility of electric load. From this viewpoint, electrical energy storage systems [13,14] and electrical heating with heat storage (HS) systems [15,16] have been developed and implemented to enlarge the adjustability of electric load. However, the performances of these systems are limited, since the electric energy is difficult to store on a large scale [17,18], and transforming electrical energy to thermal energy commonly leads to little economic benefit according to the 2nd law of thermodynamics. An alternative way to improve the flexibility of power system is to improve the adjustability of electric sources. For the CHP systems, introducing HS facilities becomes a feasible solution [19–23], which decouples the heat supply and the heat load, and consequently decouples the power generation and the heat load in a CHP system. In the previous studies, sensible HS facilities are

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Nomenclature

A	area, m^2
c	specific heat capacity, kJ/(kg·K)
D	down ramp rate, MW/min
k	heat transfer coefficient, MW/(m^2·K)
m	mass flow rate, kg/s
P	power, MW
Q	heat transfer rate, MW
R	thermal resistance, K/MW
r	latent heat, MJ/kg
T	temperature, °C
t	time, h
U	up ramp rate, MW/min
α	ratio, (kg/s)/MW
β	heat-electricity ratio, MW/MW
Φ	amount of heat stored in the HS facility, MWh
φ_{loss}	heat loss rate, %/h

Subscripts

c	cold fluid
chp	combined heat and power plant
HES	heat exchanger station
HS	heat storage facility
h	hot fluid
i	inlet
load	user load
m	middle
max	maximum
min	minimum
oil	heat conduction oil
o	outlet
phase	phase-change
rel	release heat exchanger
s	steam
sto	storage heat exchanger
tpp	thermal power plant
w	water
wind	wind power plant

widely applied in the heating systems, especially by using water as the HS medium [24,25]. However, due to the limited variation range of water temperature, the HS density is relatively lower. In this case, latent HS facilities with phase-change materials will be preferable, as the technology of large capacity phase-change thermal storage has become increasingly mature [26].

In addition, in order to fully improve the adjustability of CHP system with HS facility, both the electrical and the heat transmission processes need to be analyzed as a whole. However, the different characteristics of electrical and thermal energy in transmission lead to the obstacle for the global analysis of the whole integrated systems. That is, the research perspective of electrical system is the "power flow", whereas that of thermal system is the "working fluid flow". As a result, the conventional solution is to simplify the thermal systems as the boundaries of power system, where only the external characteristics are considered. For instance, such simplification was applied in Refs. [27–34] to study the feasibilities [27–29] and optimize the performance [30–34] of different integrated energy systems with HS facilities, respectively. However, ignoring detailed heat transfer processes will bring some inaccuracy, especially when the actual working status of thermal systems deviates from the rated status significantly. Recently, some scholars began to work on the analogy study between heat and electricity, in order to set up an overall model for both thermal and electrical systems [35–38]. They remodeled heat exchangers [35–37] and heat exchange networks [38] in the form of electric circuit, which provided the possibility to analyze the integrated thermal and power systems as a whole.

In this contribution, we focus on an integrated thermal and power system consisting of a wind power plant, a thermal power plant and a CHP plant, where the curtailment of wind power is quite serious in the heating season. In order to enlarge the wind energy integration, we put forward a new proposal for increasing the flexibility of the system by using latent HS facility with phase-change material. The heat transfer and storage processes in the system are analyzed by the entransy dissipation-based thermal resistance method proposed in Refs. [36–38], which takes the heat transfer processes in the HS facility into account. On this basis, the operation mode of the integrated system is optimized to maximize the accommodation of wind power by using the linear programing (LP) method. Finally, the influence of some design parameters of the HS facility on the system performance is further discussed.

2. An integrated thermal and power system and its physical models

2.1. Introduction of the integrated system

Fig. 1 shows the physical model of an integrated thermal and power system concerned in this paper. It contains such three different power plants as a wind power plant, a thermal power plant and an extraction condensing CHP plant, which is divided into two subsystems. For the electrical subsystem, electricity generated from the three plants transfers through the power system to satisfy the electric load. For the thermal subsystem, heat generated by the CHP plant transfers through the heat exchanger station (HES) and other parts of the district heating (DH) system to satisfy the heat load, where the heat transfer medium is water. In addition, different from the traditional CHP-based DH system, there is an HS facility installed in the CHP plant with two additional counter-flow heat exchangers (B and C) and an additional two-branch fluid loop (III). Heat conduction oil is selected as the working medium in the additional loop, and a suitable phase-change material is chosen as the substance filled in the HS facility due to the high heat storage capacity. Meanwhile, the phase-change material exchanges heat with the heat conduction oil in the HS facility. By opening/closing the valves, the system has two alternative work modes:

1) When the Valves a and b open and the Valves c and d close, the heat released from the extraction steam is transferred to the heat conduction oil through the storage heat exchanger and then stored by the phase-change material in the HS facility;
2) When the Valves c and d open and the Valves a and b close, the heat released from the phase-change material in the HS facility is transferred to the heat conduction oil and then absorbed by the water in the release heat exchanger of the DH system.

Overall, the latent HS facility stores heat from the extraction steam and releases heat to the back water. It makes full use of the temperature difference between the steam and the water to enhance the efficiency of both heat exchange processes.

As shown in Fig. 1, the steam extracted from the CHP plant flows