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Peak shaving operational optimization of supercritical coal-fired power plants by revising control strategy for water-fuel ratio

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HIGHLIGHTS

- A water fuel ratio control strategy was proposed based on heat storage deviation.
- Several indexes were proposed for describing the peak shaving operational features.
- Accumulation deviations of main parameters in load cycling were reduced.
- Flexibility and economic performances of a supercritical unit were improved.

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ABSTRACT

Electricity generated from renewable energy source fluctuates heavily and can hardly be predicted. The peak shaving (or load cycling) operation of conventional thermal power plants is an effective means to mitigate the mismatch between electricity demands and supplies. Therefore, determining how thermal power plants can operate in a flexible and effective mode is an urgent issue that should be addressed. For thermal power plants, new methods and strategies need to be proposed to face the challenge of the integrating flexibility and energy saving into transient processes. Dynamic performances of thermal power plants during load cycling processes are affected by the coupling of the thermal system and the control system. Feasible approaches from optimizing the coordinated control system (CCS) may radically enhance the peak shaving capacity of thermal power plants. The heat storage in a coal-fired power plant, including heating surface metals and work media, varies with the load rate of the plant. During cycling load operations, the real-time heat storage value of one unit differs from that of the corresponding steady state load command rate. This difference hinders the flexibility of one unit and affects its economic performances during cycling processes. In this paper, a revised water fuel ratio (WFR) control strategy based on heat storage difference was proposed and tested on established coal-fired power plant models. Results show that the accumulation deviations of load rate command and real-time load rate are considerably reduced during load cycling processes when the proposed WFR control strategy is introduced. The revised WFR control strategy diminishes the difference between the target and the actual total power output. When the load cycling rate varies from 10 to 30 MW min^{-1} between 50% and 100% THA, the standard coal consumption variation rate (Δb_s) decreases by 0.31–1.01 g $kW^{-1} h^{-1}$ during loading up processes, and decreases by 0.26–1.69 g $kW^{-1} h^{-1}$ during loading down processes.

1. Introduction

1.1. Research background

In recent years, a growing number of countries are encouraging the development of power plants fed by renewable energy sources (RES) to alleviate the reliance on fossil fuels and adequately protect environment [1–3]. For example, Germany aims to increase the share of renewable sources to at least 80% of the gross power consumption by 2050 [4,5]. In addition, former US president Barack Obama [6] concluded that the trend toward clean energy is irreversible in the US by analyzing the economic development, carbon dioxide emissions and power sector market forces. Consequently, a high penetration of power plants fed by unpredictable RES will have significant impacts on the electricity market [7]. Electricity generated from RES, such as wind, solar, geothermal and tidal resources, exhibits the following features: intermittent, cyclical and constrained by geography [8–11]. Therefore, power systems require new solutions that can guarantee high

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Nomenclature

Abbreviations

b	generation coal consumption rate
B	mass of coal consumption
c	specific heat capacity
e	relative deviation of transient and stationary value
h	gas or liquid enthalpy
M	gas or liquid mass in control volume
p	pressure
P	generated power output
Q	heat storage/low heating value
T	liquid or gas temperature
TPO	total power output
THA	turbine heat acceptance
V	cycling load rate
W	total power output
WFR	water fuel ratio
X	accumulation deviation

Greek symbols

τ	time/dimensionless time
Δ/δ	difference

Subscripts

g	flue gas
m	metal
mst	main steam temperature
rht	reheat steam temperature
r-t	real time value
p	constant pressure
s	steam/standard value
s-p	set point value
t	total

operational flexibility to balance electrical supplies and demands while maintaining high energy conversion efficiency [7,12]. An increasing number of traditional thermal power plants fed by fossil fuel are being required to compensate for RES [13,14]. In Europe, load cycling are undertaken by combined cycle power plants [15]. As outlined by Balling [16], the conventional power plants in Germany will have to be started up and shut down several times weekly, or even daily in the next 5 years. Schill et al. [5] asserted that the relevance of start-up costs may increase further under continued renewable expansion, but may be mitigated by increasing system flexibility. In China, a growing number of coal-fired power plants will frequently operate in cycling operation modes. Therefore, the time of cycling load from one steady running state to another running state, which is attributed to the substantial thermal inertia of the coal-fired power plants, must be considered. Moreover, with the frequent load cycling demands from grid dispatching centers, energy saving is encouraged for power plants transient operations. Therefore, improving the flexibility and economic performances for a coal-fired power plant is an extremely urgent issue that should be addressed.

1.2. Literature review

To overcome the peak shaving challenge from electricity demands, a number of concerted efforts have been made in recent years to improve the power plants operational flexibility and economic performances [3,17,18]. For RES power plants, energy storage technology appears indispensable for their regular operations [19]. Amrouche et al. [20] asserted that energy storage is a dominant factor in the integration of renewable sources, and it plays a significant role in maintaining a robust and reliable modern electricity system. Pelay et al. [19] presented a review on the thermal energy storage systems installed in concentrated solar power (CSP) plants. The sensible heat storage system is the most popular type among the majority of CSP plants because of its operational reliability, low cost and available numerous experimental results. For traditional thermal power plants, energy storage technology is also vital for load cycling processes. The energy storage technology, mainly including flywheels, super capacity/conventional batteries, compressed air, pumped hydro and thermal energy storage [20–22], is an effective solution for facilitating RES integration by absorbing or releasing energy immediately in response to the system needs [23]. Garbrecht et al. [24] performed studies to investigate the use of molten-salt storage systems in fossil-fired power plants by conducting a series of numerical process simulations. Their study results showed that the implementation of a thermal storage system in order to contribute to grid stability is a promising option. However some disadvantages of this system are as following: high-cost, maintenance-intensive, and complex. The integration of heat pumps (HPs) into thermal plants to generate large-scale electricity storage capacities is an another promising method to explore the potential of operational flexibility. Vinnemeier et al. [25] presented a pumped heat electricity storage systems, and conducted a thermodynamic assessment approach based on exergetic quantities. The storage size mainly influences the duration of the flexibility supply and thus the energy flexibility per cycle. Stinner et al. [26] quantified the operational flexibility of building energy systems with thermal energy storages, which indicates that combined heat and power (CHP) plants can offer higher flexibilities compared to HPs with the same storage volume and the same assumed thermal power.

The thermal system of the coal fired power plant has large heat storage in the boiler and the regenerative system. Heat storage can be taken full advantage of during peak shaving operations. Liu et al. [27,28] proposed the combination of the condensate throttling method and coordinated control to accelerate the load response. They also investigated on the energy storage and quick load change control of subcritical circulating fluidized bed (CFB) boiler units [29]. In their paper, an advanced energy balance is designed to shorten the response time by using the energy storage and accelerating the load change speed of subcritical CFB units. A case study on a 300 MW CFB boiler unit proves the feasibility of the proposed control strategy. Zhou et al. [30,31] proposed a new conception of radiative energy signal in the coal-fired boiler and optimized the boiler combustion of a coal fired power plant. The results show that better combustion efficiency can be obtained in association with the control property. Moreover, a decrease in fuel consumption with a corresponding decrease in the energy consumption and a reduction of emissions, has been studied and tested for the optimization. ŁukaszS' ladewski et al. [32] optimized the combustion process in coal-fired power plant with utilization by using an acoustic system for in-furnace temperature measurement integrated with distributed control system.

1.3. Novelty and contribution

The literature review indicates that studies on improving the flexibility and optimization on CCS of the thermal power plant have attracted some researchers' attentions in recent years. However, the energy consumption characteristics and energy saving methods of the thermal power plant during transients are scarce but necessary. The energy conversion processes of the coal fired power plant are influenced by its thermodynamic states. The thermal inertia of a coal fired power