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Study of supercritical power plant integration with high temperature thermal energy storage for flexible operation

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ABSTRACT

The paper presents the recent research in study of the strategies for the power plant flexible operation to serve the requirement of grid frequency control and load balance. The study aims to investigate whether it is feasible to bring the High Temperature Thermal Storage (HTTS) to the thermal power plant steam-water cycle, to identify the suitable thermal charge and discharge locations in the cycle and to test how the HTTS integration can help support grid operation via power plant dynamic mathematical modelling and simulation. The simulation software named SimuEngine is adopted and a 600 MW supercritical coal-fired power plant model is implemented onto the software platform. Three HTTS charging strategies and two HTTS discharging strategies are proposed and tested via the simulation platform. The simulation results show that it is feasible to extract steam from the steam turbine to charge the HTTS, and to discharge the stored thermal energy back to the power generation processes. With the integration of the HTTS charge and discharge processes, the power plant simulation model is also connected to a simplified GB (Great Britain) grid model. Then the study is extended to test the improved capability of the plant flexible operation in supporting the responses to the grid load demand changes. The simulation results demonstrate that the power plant with HTTS integration has faster dynamic responses to the load demand changes and, in turn, faster response to grid frequency services.

1. Introduction

The current balance between power generation and load demand is mainly managed through regulating the output of fossil fuel power plants. With the rapid increase of power generation from renewable energy, fossil fuel power plants are required to play more important role in maintaining load balance and providing the grid frequency control service as they are considered as dispatchable power generation units. Fossil fuel power plants are now required to work more flexibly, responding faster with more frequent start-ups or shut-downs for maintaining power network stability; this can cause two serious issues: low plant efficiency and low load factors. To address these issues, it is essential to explore new technologies and operation strategies. The paper reports the recent research progress in the integration of High Temperature Thermal Storage (HTTS) with a supercritical boiler power plant to enable the power plant cycle to operate more flexibly while maintaining its thermal efficiency.

The concept of using Thermal Energy Storage (TES) for regulating the thermal plant power generation was initially reported in [1] decades ago. Several studies [2,3] were recently reported on incorporation of TES into Combined Heat and Power (CHP) generations, in which TES is used to regulate the balance of the demand for heat and electricity supply. A report indicates that a high temperature latent heat TES unit is to be built in an operating cogeneration plant in Saarland, Germany [4]. In this planned power station, HTTS produces superheated steam to industrial customers in an emergency. Also, many studies have been reported in the area of solar thermal power plant integration with TES, in which TES plays an important role to time shifting of energy delivery in an economic way [5–9]. Besides, the study of a combined-cycle gas turbine power plant combined with TES in order to improve the plant flexibility is presented in [10]. Moreover, Wojcik [11] presented a feasibility study of TES integration with a 375 MW subcritical oil-fired conventional power plant for flexible operation.

For the supercritical coal-fired power plant, the flexible operation is the rapid power response capability for satisfying frequency control. The boiler turbine coordinated control is a widely adopted control strategy to regulate power generation in thermal power plants. However, the plant dynamic response is slow due to the large time delay of the energy transfer from the fuel supply to the water-steam loop [12]. A revised water fuel ratio control strategy was proposed by Wang to enhance the peak shaving capacity of supercritical coal-fired power plant [13]. Besides, Zhao proposed a method for improving the

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Nomenclature

Abbreviations

CHP	Combined Heat and Power
GB	Great Britain
HTF	Heat Transfer Fluid
HTTS	High Temperature Thermal Storage
IPTB	Intermediate Pressure Turbine
LPTB	Low Pressure Turbine
TES	Thermal Energy Storage

Symbols

C_{CND1}	Minimum heat transfer coefficient of saturated section
C_{CND2}	Heat transfer coefficient of saturated section
C_{DRN1}	Minimum heat transfer coefficient of drain cooling section
C_{DRN2}	Heat transfer coefficient of drain cooling section
C_{DS1}	Minimum heat transfer coefficient of superheat section
C_{DS2}	Heat transfer coefficient of superheat section
C_{pm}	Specific heat of water
$E_{kinetic}$	Stored kinetic energy of a synchronous machine
D	Load response $kg{\cdot}m^2$
f_0	Grid normal frequency Hz
h	Enthalpy $kJ{\cdot}kg^{-1}$
h'	Saturated water enthalpy $kJ{\cdot}kg^{-1}$
J	System inertia
K_a,K_{da}	Heat dissipation to the atmosphere, Heat dissipation of drain cooling secti$kJ{\cdot}K^{-1}{\cdot}s^{-1}$
K_f	Pipedirty influence coefficient
$\overline{K}_{Lcond}$	Condensatelevel influence coefficient when pipe exposes in steam
$\overline{K}_{LDRN}$	Condensatelevel influence coefficient when pipe submerge in water
$K_{LD\sup}$	Superheatsection coefficient
K_{wa}	Heat dissipation of water $kJ{\cdot}K^{-1}{\cdot}s^{-1}$
L	Enthalpy of phase change $kJ{\cdot}kg^{-1}$
M_m	Totalquality of pipe kg
M_{PCM}	Mass of PCM
P	Pressure Pa
ΔP	Pressure head of inlet and outlet, Pa
$Q_{storage}$	Stored thermal energy$J$
r_0	Resistance factor when valve opening is k, and temperature is 0°C
r_{00}	Resistance factor when valve opening is 1, and temperature is 0°C
s	Entropy$kJ{\cdot}kg^{-1}{\cdot}K^{-1}$
S_i	Normal power of the i-th generation unit
S_{rated}	Nominal power rating
T	Temperature
T_m	Atmosphere temperature°C
T_s	Temperature in shell side °C
V	Volume m^3
V_s, V_w	Valid volume of shell, Valid volume of pipe m^3
W	Water/steam flow rate $kg{\cdot}s^{-1}$
ρ	Density $kg{\cdot}m^{-3}$
ρ_s, ρ_w	Density in shell side, Density of water $kg{\cdot}m^{-3}$

Subscript

a	Atmosphere
de,dl	Drain water entrance, Drain water
lk	Pipe leakage
s	Steam
sat	Saturation
se	Steamentrance
w	Water
we,wl	Feed water entrance, Feed water outlet

operational flexibility of a supercritical coal-fired power plant by regulation extraction steam of high pressure heaters [14]. In summary, the previous studies focused on improving the control strategies to achieve the operational flexibility of power plant.

On the other hand, the thermal inertia of the once-through boiler is smaller than natural circulation boiler, so the capability of offering primary frequency reserve is decreased. This motivates to utilize the HTTS in the supercritical coal-fired power plant to provide an

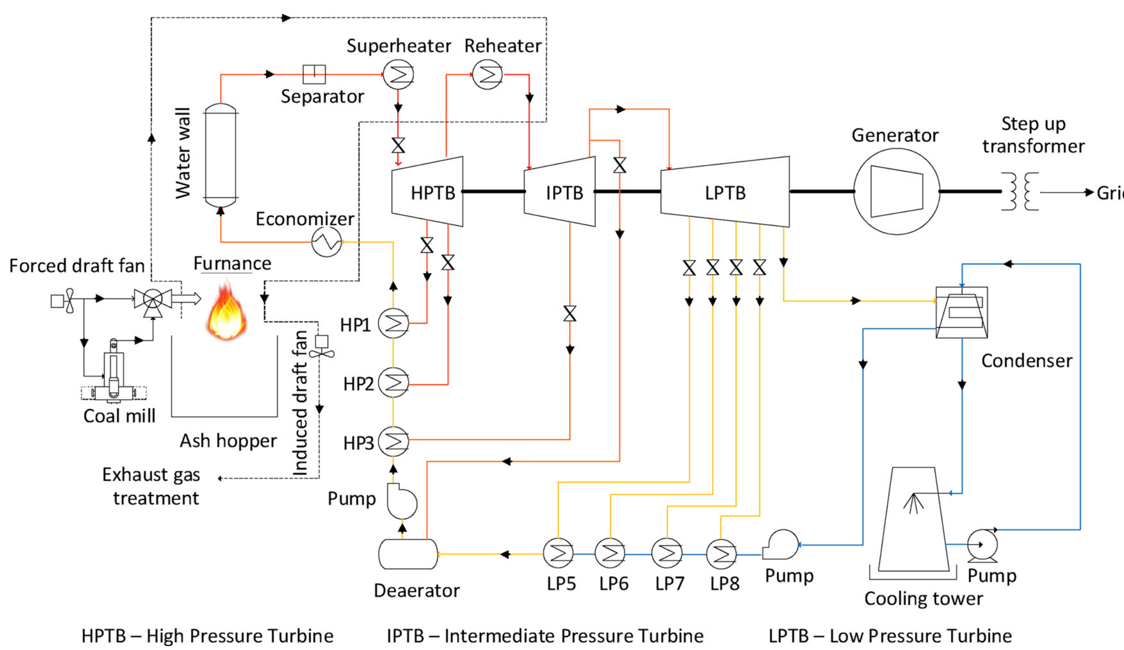

Fig. 1. Schematic of typical supercritical boiler coal-fired power plant.