Provisional chapter

Flexible Operation of Supercritical Power Plant via Integration of Thermal Energy Storage

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Additional information is available at the end of the chapter

Abstract

This chapter presents the recent research on various strategies for power plant flexible operations to meet the requirements of load balance. The aim of this study is to investigate whether it is feasible to integrate the thermal energy storage (TES) with the thermal power plant steam-water cycle. Optional thermal charge and discharge locations in the cycle have been proposed and compared. Dynamic modeling and simulations have been carried out to demonstrate the capability of TES integration in supporting the flexible operation of the power plant. The simulation software named SimuEngine is adopted, and a 600 MW supercritical coal-fired power plant model is implemented onto the software platform. Three TES charging strategies and two TES discharging strategies are proposed and verified via the simulation platform. The simulation results show that it is feasible to extract steam from steam turbines to charge the TES and to discharge the stored thermal energy back to the power generation processes. The improved capability of the plant flexible operation is further studied in supporting the responses to the grid load demand changes. The results demonstrated that the TES integration has led to much faster and more flexible responses to the load demand changes.

Keywords: supercritical coal-fired power plant, SimuEngine, thermal energy storage, flexible operation, load shifting

1. Introduction

The current balance between power generation and load demand is mainly managed by regulating the output of fossil fuel power plants [1, 2]. With the rapid increase of power generation from renewable energy, fossil fuel power plants are required to play a 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 flexible and to respond faster with more frequent start-ups or shutdowns 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.

Currently, approximately 39% of global electricity is generated from hard coal, which however produces a large amount of ash, nitrogen oxide, and carbon dioxide. The supercritical boiler was first developed in the US in the 1950s [3], which was a type of technology with improved efficiency and hence reduced carbon dioxide and toxic emissions per unit of electrical energy generation.

The flexible operation is needed for supercritical coal-fired power plants to stabilize the grid frequency. The flexibility of a supercritical power plant can be achieved by a carbon capture facility, which is used to control capture rates in response to variable load demand and carbon prices [4–7]. A method called 'condensate throttling', proposed in [8], could rapidly increase or decrease the power output of a plant. Additionally, the regulation of extracted steam for high-pressure heater could be used to enhance the primary control reserves and to offer the operational flexibility [9, 10].

The boiler turbine coordinated control is a popular control strategy to regulate power generation in thermal power plants. However, the plant response is slow due to the large delay of the energy transfer from the fuel supply to the water-steam loop [10]. Furthermore, because the thermal inertia of a once-through boiler is smaller than a natural circulation boiler, the capability of offering primary frequency reserve is decreased. This motivates the utilization of TES in supercritical coal-fired power plants, as the TES could provide the additional thermal reserve.

Currently, the TES has been widely used in various thermal power plants for flexible plant operation. Several studies [11, 12] were reported on the integration of TES into combined heat and power (CHP) generations. Also, the study of a combined-cycle gas turbine (CCGT) power plant combined with TES in order to improve the plant flexibility was presented in [13]. Besides, many studies have been reported in the area of solar thermal power plants integrated with TES, in which TES is used for time shifting of energy delivery in an economic way [14, 15].

This chapter presents flexible operation of a supercritical coal-fired power plant via the TES integration. Section 2 describes the structure and operation of a supercritical coal-fired power plant and the simulation platform used for this study. Section 3 discusses the integration strategies of TES with the supercritical power plant. Section 4 presents the improved operational flexibility of supercritical power plant when integrating with TES. Section 5 gives the concluding remarks.

2. Description of a supercritical power plant and simulation platform

A thermal steam power plant generates electricity by transforming various types of energy fuel sources making use of an idealized thermodynamic cycle called the "Rankine cycle." The

Carnot efficiency dictates that the thermal efficiency of a power plant is mainly dominated by the temperature and pressure of the steam entering the steam turbines. Above the critical point for water at 374.15°C and 22.12 MPa, there is no phase transition from water to steam. A sub-critical coal-fired power plant with water/steam working under the critical point typically has an efficiency between 33 and 39%. In comparison, a supercritical or ultra-supercritical power plant can achieve a much higher efficiency of up to 48% [1]. Therefore, supercritical power plants have been extensively developed since the 1950s and constructed worldwide, thanks to the simultaneous development of novel materials and components which can withstand high pressure/temperature and adverse working conditions.

A simplified schematic of a typical supercritical coal-fired power plant is illustrated in **Figure 1**. The pulverized coal from the mill is burnt in the boiler furnace, releasing combustion heat to the feed water coming from the Economizer. During elevation of the water inside the water wall and superheater exchanger tubes, the water is transferred directly to the supercritical steam without evaporation. Unlike a subcritical power plant, a drum is not a necessary component in the so-called once-through boiler and it can be replaced by a smaller steam-water separator acting as the drum's role in the consideration of low load working conditions. A reheater is used to absorb the heat from downstream flue gas and reheat the exhaust steam from the high pressure (HP) turbine before it enters the intermediate pressure (IP) turbine. Several streams of steam are extracted from different locations of HP, IP, and low-pressure (LP) turbines to preheat the feed water.

An industrial 600 MW supercritical coal-fired power plant has been used as a reference plant in this study. The on-site measurement data including temperature, pressure, and mass flow rates of the water/steam at different locations under the nominal power output of 600 MW have been collected and summarized in **Table 1**.

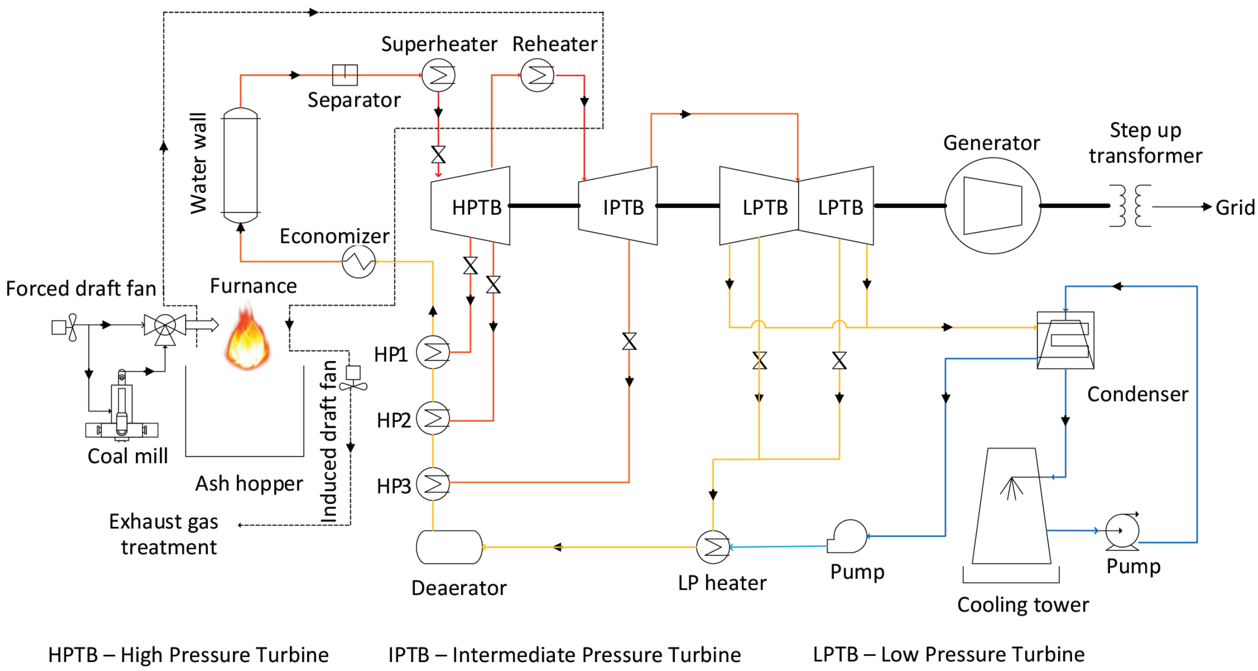

Figure 1. Simplified schematic of a supercritical coal-fired power plant.

	Temperature (°C)	Pressure (MPa)	Flow rate (kg/s)
HP heater inlet	166.86	27.65	484
HP heater outlet	263.49	27.48	484
Economizer outlet	312.63	27.3	484
Super heater outlet/HPTB inlet	562.04	25.1	483.9
HPTB outlet	304.72	4.41	445.9
IPTB inlet	565.66	3.8	406.4
IPTB outlet	354.86	0.9	387.2
LPTB inlet	354.86	0.9	309.2

Table 1. Main water/steam parameters in a 600 MW supercritical coal-fired power plant.

In principle, a power plant model can be established based on the energy and mass conservation equations for different components in the power plant system [9, 16].

Mass balance:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v)}{dz} = 0. \tag{1}$$

Energy balance:

$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho v h)}{\partial z} = \frac{\partial p}{\partial t} + Q, \tag{2}$$

where, ρ, v, h, p are the density, velocity, enthalpy, and pressure of the working fluid in the specific control volume respectively, and Q is the heat flow across the boundary of the control volume.

To perform the off-line tests with the optional control mechanism and dynamic responses for a practical power plant, a more detailed and visualized simulation platform called SimuEngine was initially developed by Tsinghua University, China and then further exploited in the University of Warwick, UK. The supercritical power plant model implemented on the SimuEngine can deal with a complex flow net, which represents a typical power plant system consisting of resistance component (such as valves), power components (such as fans), inertia node and source-sink nodes. The joints in a flow net are defined as nodes, while the channels connected with the nodes are defined as branches. Node pressure method is applied to solve the nonlinear flow net equations in order to obtain the nodes' pressure and flow rates of the branches. The simulation results have been verified by the real operational plant data. More detailed descriptions of the fluid network models can be found in previous publications by the authors' group [17, 18].

3. TES integration strategies and results

This section presents the integration strategies and simulation results of a supercritical coal-fired power plant with TES. There are three types of TES: sensible heat storage, latent heat storage, and chemical heat storage. The latent heat storage is applied to the hybrid system, as its energy density is higher than sensible heat storage and the cost is lower than chemical heat storage.

3.1. TES charging strategies

TES charging can be realized by extracting steam from different locations of the water-steam loop of the power plant and flowing the extracted steam through heat exchangers to store thermal energy during the off-peak period. In this way, the electrical power output can be regulated while maintaining the constant heat duty of the boiler. This study is conducted to find the answers to the following challenging questions: where the TES can be integrated and how much thermal energy can be extracted without degrading the plant thermal performance? Three heat extraction (TES charging) strategies have been investigated with two optional thermal energy extraction locations, which are Intermediate Pressure Turbine (IPTB) inlet and Low Pressure Turbine (LPTB) inlet. As shown in **Table 1**, the steam temperature at IPTB inlet and LPTB inlet are around 565 and 355°C, and the pressures at these two inlets are around 3.8 and 0.9 MPa, respectively. The simulation results are presented and analyzed in the following subsections.

3.1.1. Extracting steam from IPTB and looping back to the condenser

While the steam extraction point is set at the inlet of the IPTB, the relatively high temperature steam will pass a series of heat exchangers to store the thermal energy contained in the steam. The exhaust steam at the outlet of the TES is mixed with the LPTB outlet steam and enters the condenser. The schematic of this TES charging strategy is shown in **Figure 2**.

The amount of steam extraction is controlled by the valve openings. With different valve openings, the mass flow rate of the steam entering the IPTB and LPTB is changed, as a result, the power output is reduced. The simulation results of the mass flow rates in the TES and the variations of the plant power output with different valve openings are shown in **Figure 3**.

From **Figure 3**, it is clear that the amount of the steam extraction needs to be restricted to a feasible range in order to maintain a stable power output. The simulation study indicates that the maximum flow rate of steam extraction from the IPTB inlet is 80 kg/s, and the relative reduction of the output power is 13.3% in comparison with its rated power.

3.1.2. Extracting steam from LPTB and looping back to the condenser

Instead of the IPTB inlet, the steam extraction at the inlet of LPTB is studied in this section. After the charging process, the steam will flow into the condenser mixing together with the LPTB outlet steam. The schematic of this TES charging strategy is shown in **Figure 4**.

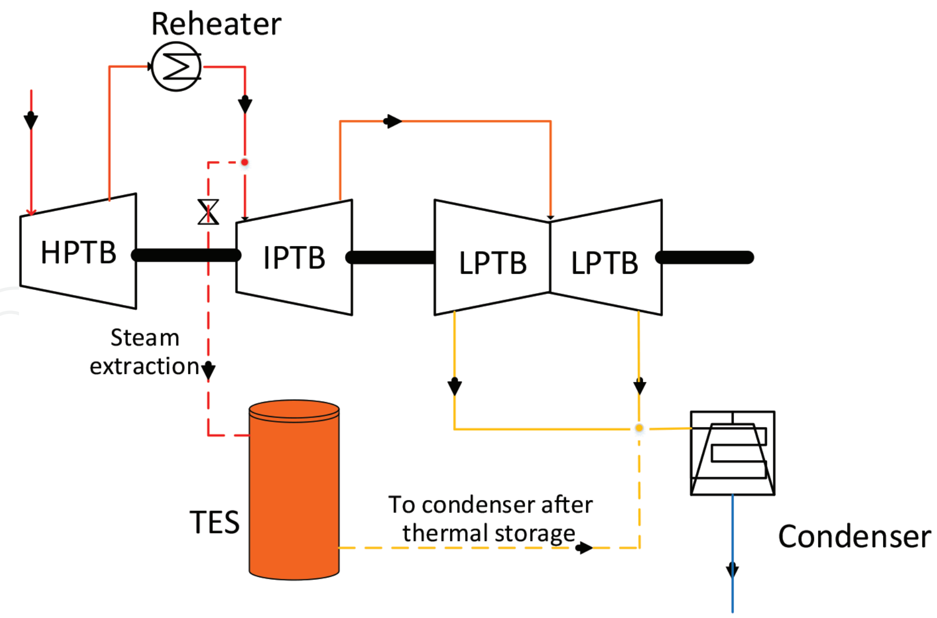

Figure 2. Schematic of the first TES charging strategy.

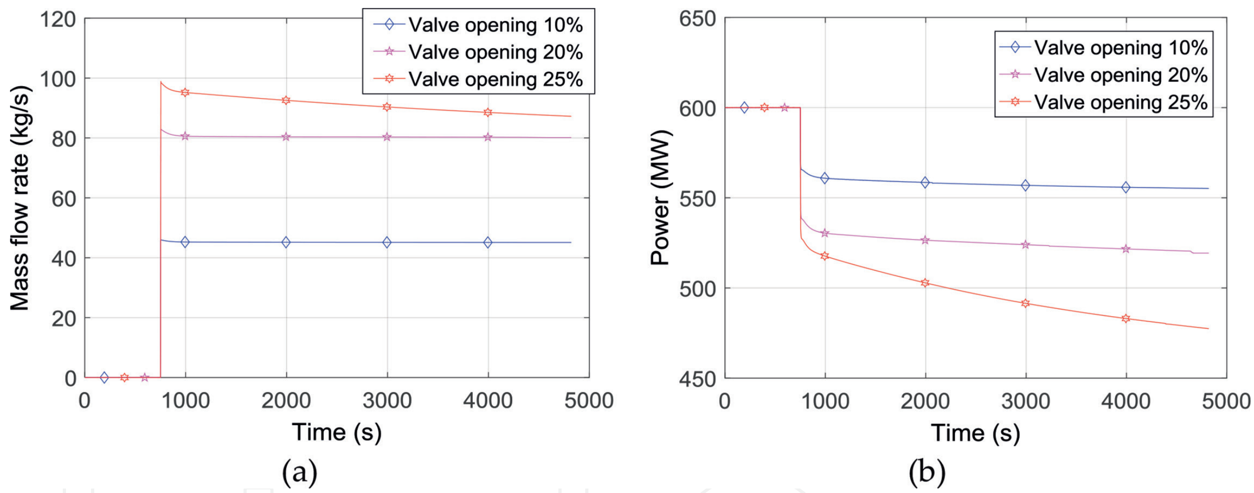

Figure 3. Dynamic responses of mass flow rate in TES and output power: (a) mass flow rate and (b) output power.

The simulation results of the mass flow rates in the TES and plant power output changes with different valve openings are shown in **Figure 5**. The simulation study indicates that in order to maintain a reasonably stable power output, the maximum rate of steam extraction from the LPTB inlet is 56 kg/s (corresponds to the valve opening of 60%), and the relative reduction of the output power is 6.5% (561 MW).

3.1.3. Extracting steam from IPTB and feeding steam back at LPTB inlet

The study reported in this section is to investigate whether the thermal storage can be controlled in order to regulate the temperature and pressure of the exhaust steam at the outlet of the TES. When the temperature of the steam is controlled to have the same value as required

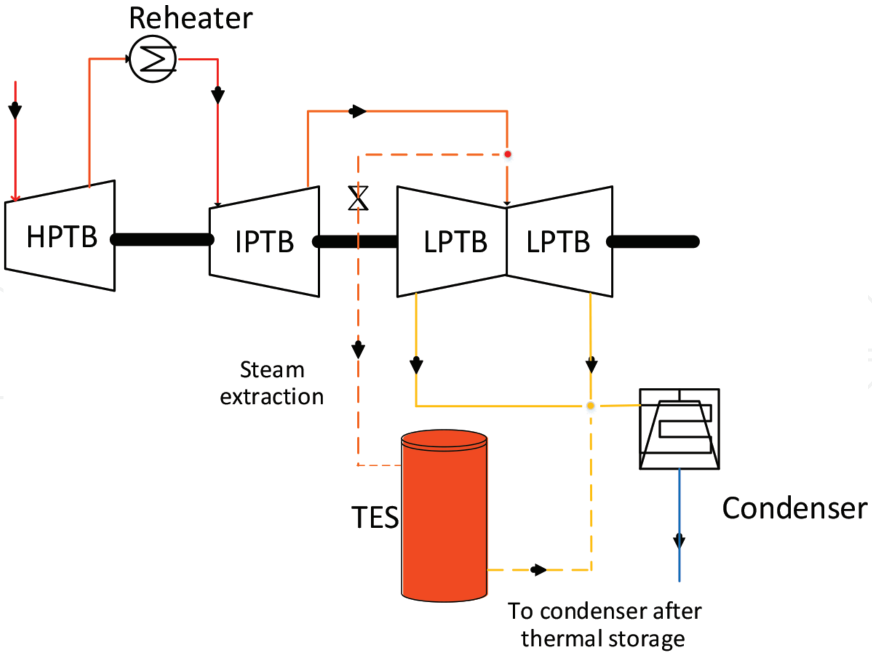

Figure 4. Schematic of the second TES charging strategy.

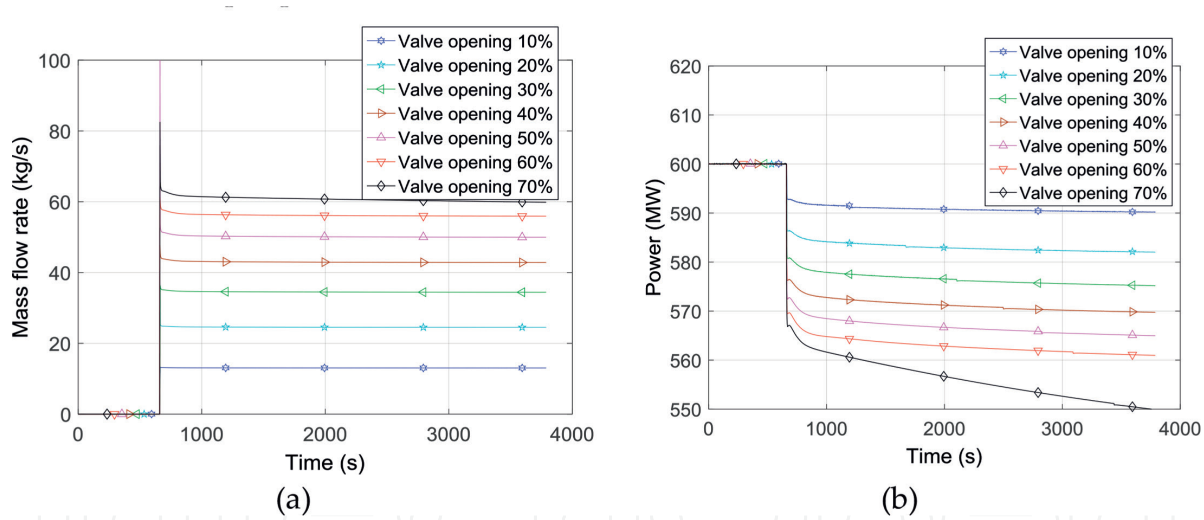

Figure 5. Dynamic responses of mass flow rate in TES and output power: (a) mass flow rate and (b) output power.

by the LPTB inlet, the steam can be fed back to the LPTB inlet directly to mix with the steam coming from IPTB. The schematic of this TES charging strategy is shown in **Figure 6**.

The simulation results of the mass flow rates in the TES and the power output associated with different valve openings are shown in **Figure 7**.

With various operating conditions and application of the above TES charging strategy, the maximum flow rate of steam which can be extracted from the inlet of IPTB is 174 kg/s (corresponds to the valve opening of 60%), and the adjustment range of the output power is 3.9% (576.5 MW). Excess extraction will lead to the steam pressure being lower than the operating

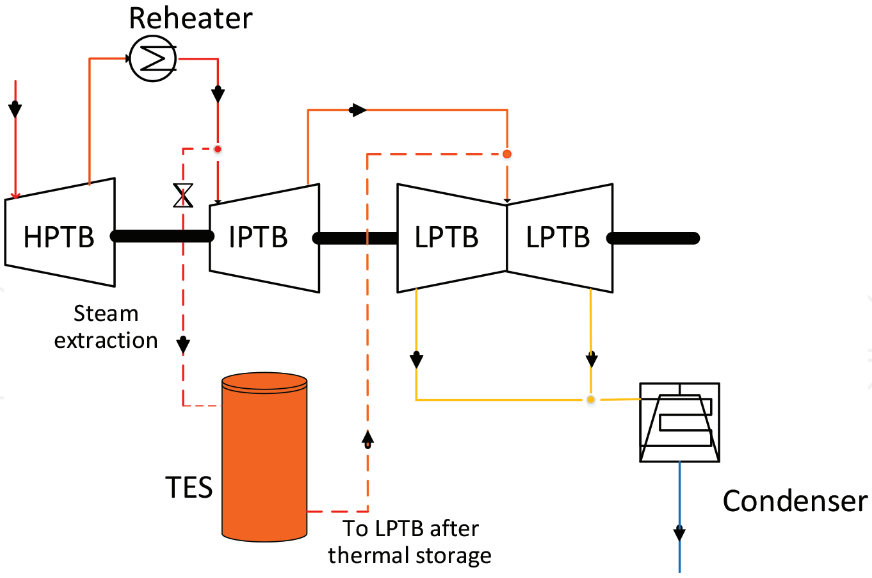

Figure 6. Schematic of the third TES charging strategy.

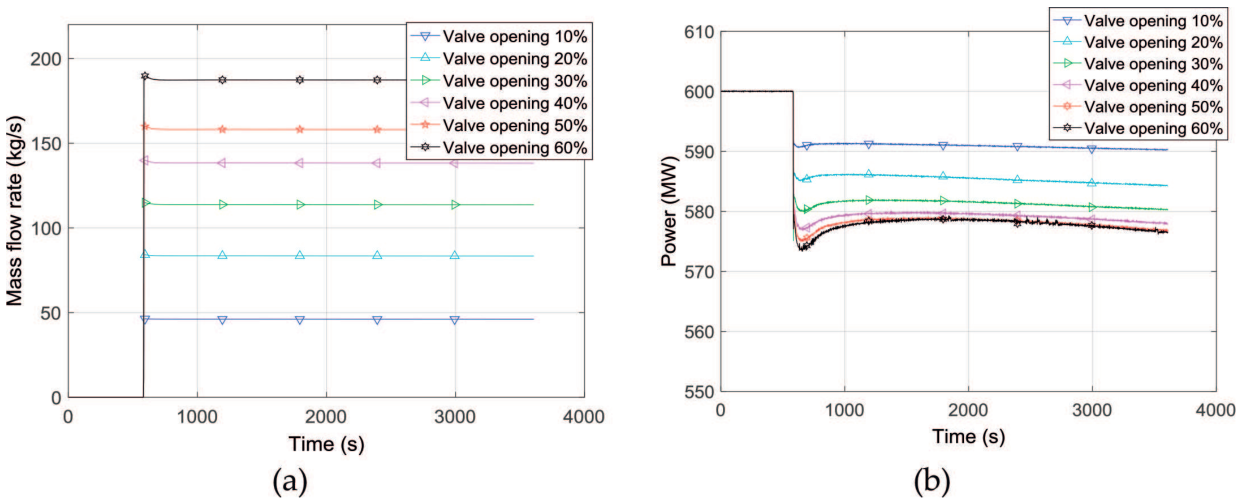

Figure 7. Dynamic responses of mass flow rate in TES and output power: (a) mass flow rate; (b) output power.

pressure required by the IPTB. So this strategy only works with a small range of power regulation. The advantage of this strategy is that the steam can be recycled back to LPTB without modifying the whole system cycle.

3.2. TES discharging strategies

During the electricity peak demand period, the stored thermal energy in the TES will be discharged back to the water steam loop to increase the total electricity generation. Two strategies have been studied: the first one is to use TES to produce high temperature and high-pressure steam, which is then fed into the LPTB inlet; another is to use TES to preheat the feed water instead of using the original preheaters. The simulation study for these two strategies is presented and analyzed in the following subsections.

3.2.1. Using TES to produce additional steam for LPTB

During the TES discharging process, part of the feed water flows into the bottom of the TES section from the deaerator, evaporates into steam and is superheated while it rises along the heat exchanger tubes in the TES, then it leaves the TES in the status of superheated steam. Heat is transferred from the TES to increase the temperature of the water/steam passing through the tubes. The steam is then fed to the LPTB inlet and produces an additional electric power output. As part of the feed water is taken out of the deaerator, more water is needed to be pumped into the deaerator in order to maintain the steam flow rates in the HPTB and IPTB. **Figure 8** shows the schematic diagram of the proposed TES discharging strategy.

Figure 9 shows the simulation results of power output with the heat discharge. With various valve openings, the increased steam flow rate and power output are observed. From the simulation study, the maximum flow rate of the steam generated from the TES is 72.6 kg/s. As a result, the corresponding overall output power is 644.4 MW, which nearly approaches the design limit of the power plant.

3.2.2. Using TES to heat feed water instead of preheaters

In a coal-fired supercritical power plant, part of the steam is taken out from the steam turbines to preheat the feed water, as shown in **Figure 10**. In this supercritical coal-fired power plant, there are three HP heaters and a group of LP heater. The steam taken out from the HPTB is used for No. 1 and No. 2 HP heaters, the extracted steam from the IPTB is used for No. 3 HP heater, and the steam taken from LPTB is used for LP heater as shown in **Figure 10**.

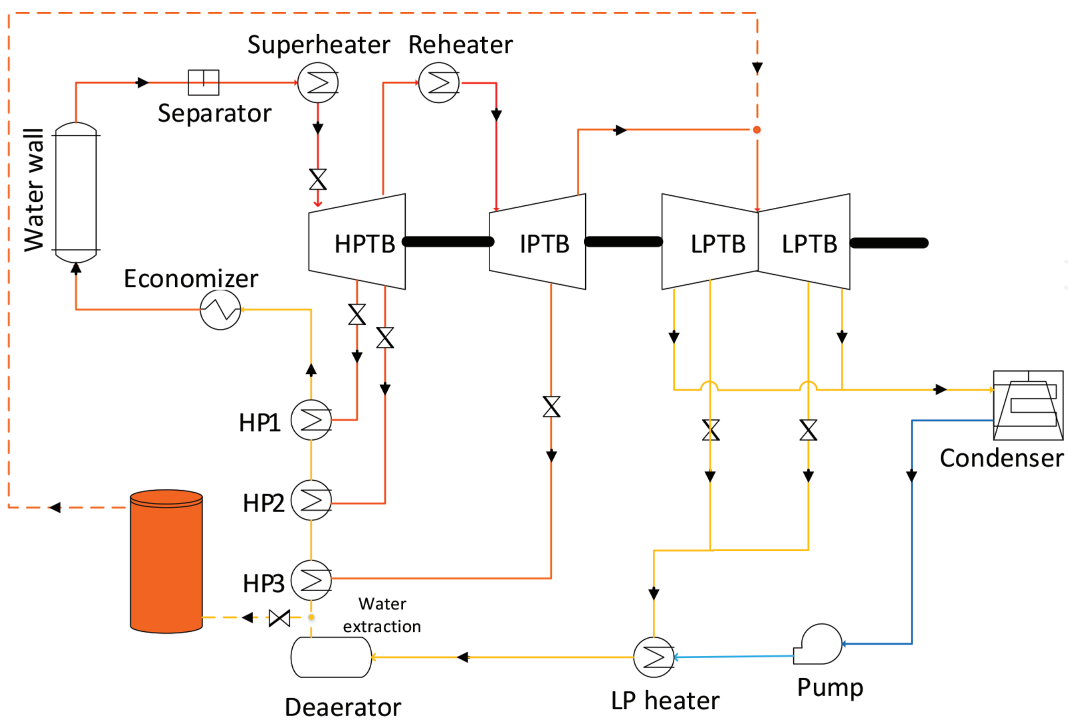

Figure 8. Schematic of the first TES discharging strategy.

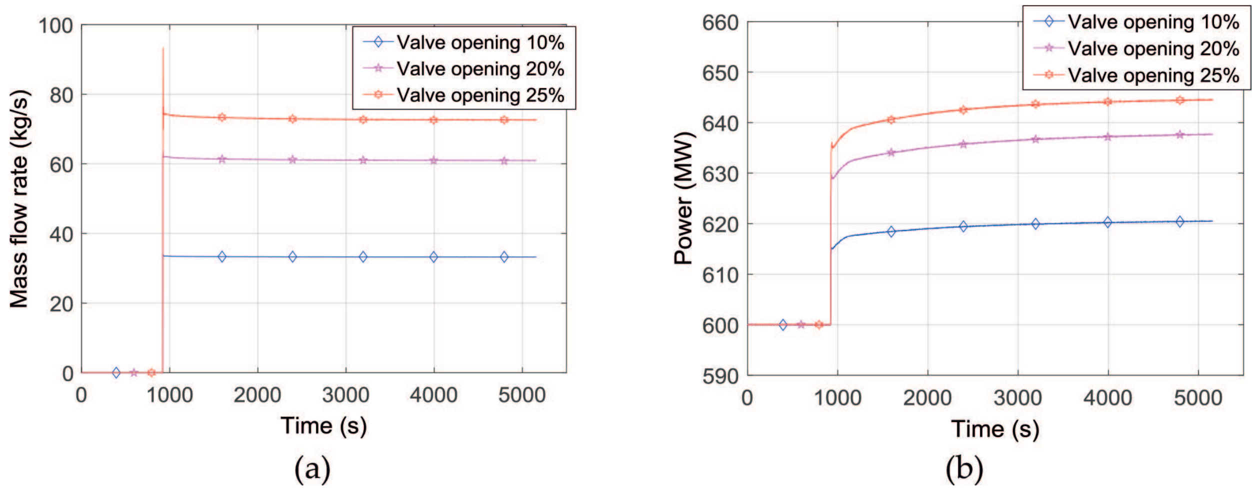

Figure 9. Dynamic responses of mass flow rate in TES and output power: (a) mass flow rate and (b) output power.

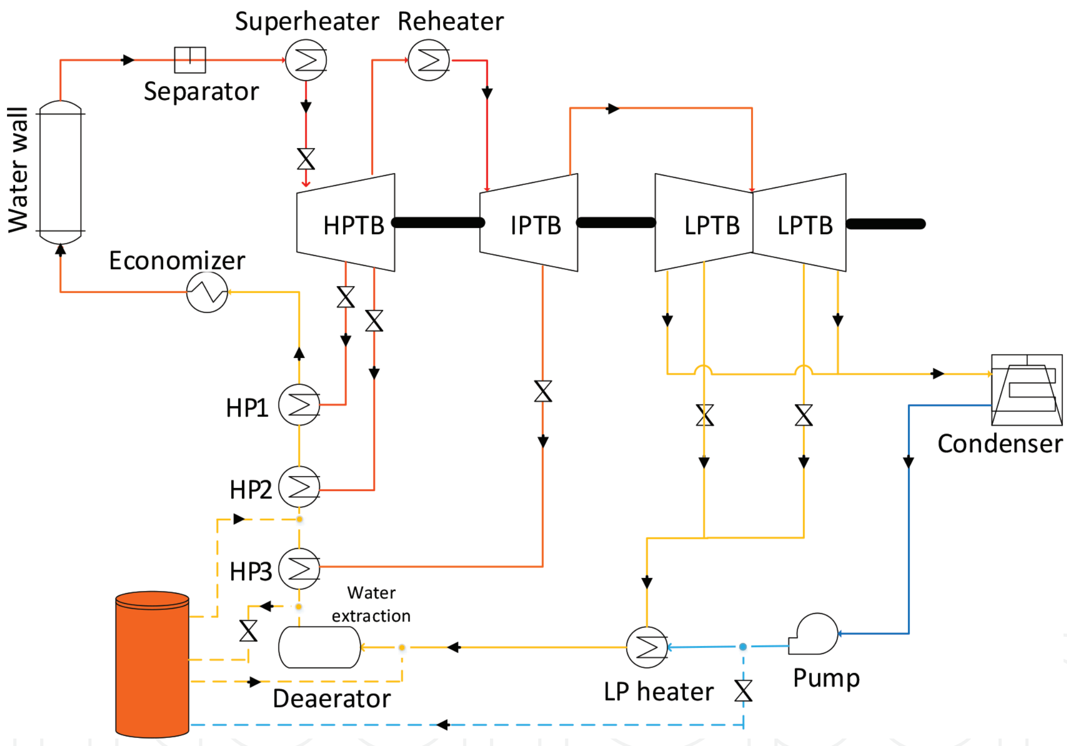

Figure 10. Schematic of the second TES discharging strategy.

The amount of the steam extraction is controlled by regulating valve openings. When these valves are closed, more steam will pass through the downstream turbines and produce more power. However, this operation leads to the decrease of the feed water temperature. With the TES integration, in order to maintain the feed water temperature, the feed water will bypass the preheaters and flow into TES to raise its temperature. Simulation results are shown in **Figure 11**.

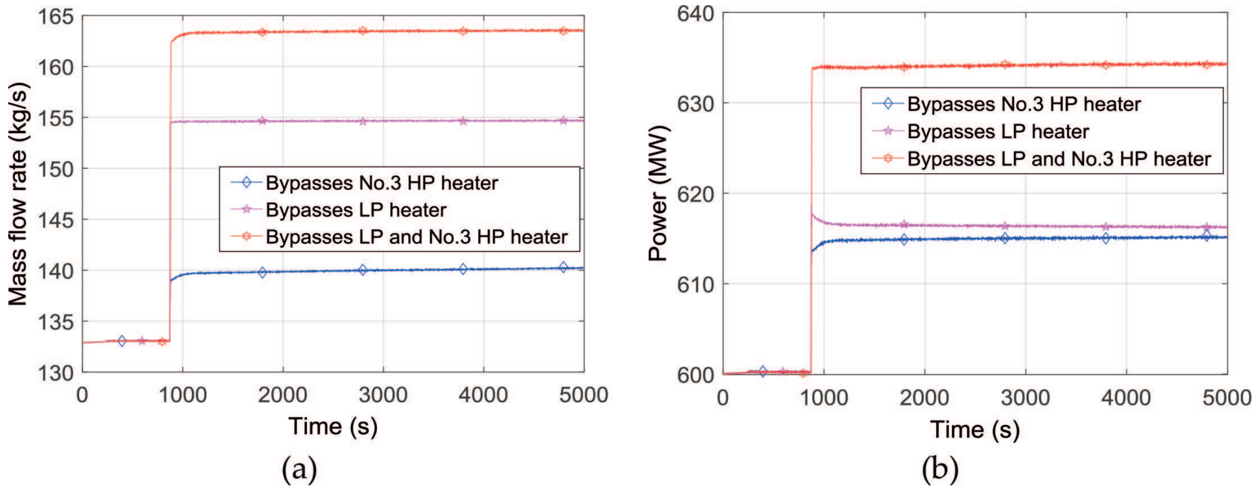

Figure 11. Using TES to heat feed water instead of preheater: (a) mass flow rate and (b) output power.

When the valve used to extract steam for No.3 HP heater is closed, the feed water will bypass the No.3 HP heater and it will be heated by the TES. Accordingly, the output power is increased to nearly 615 MW from 600 MW. When those valves for extracting steam to feed to the LP heater are closed, the feed water will bypass the LP heater and enter the TES for heating. As a result, the output power is increased to around 616.5 MW from 600 MW. When those valves for extracting steam to feed to the LP heater and No. 3 HP heater are closed, the feed water will bypass the LP heater and No. 3 HP heater and be heated by TES. Then the output power is increased to 634 MW from 600 MW. This method requires no plant structure changes so it is more feasible and cost-effective although the power regulation capability is limited to a small range.

4. Improvement in dynamic performance

The simulation results have shown that the power plant could be operated with increased flexibility within a wider range of power output through TES integration. The TES could accumulate or release thermal energy to regulate the plant power output, therefore it offers the enhanced capability in providing the services to load shifting. The dynamic performance of the supercritical power plant with or without TES integration is compared in this section.

The simulation results are shown in **Figures 12** and **13**. The solid line is the power output dynamic responses with the TES integration in action, in which the output power is regulated with the support of TES charging and discharging processes while the amount of feed coal (fuel input) remains the constant. The dashed line represents the power output without TES integration where the power output is directly controlled by changing the flow rate of coal feeding. It can be seen that the power plant integrated with TES shows faster dynamic responses and smoother transitions compared with the power plant without TES.

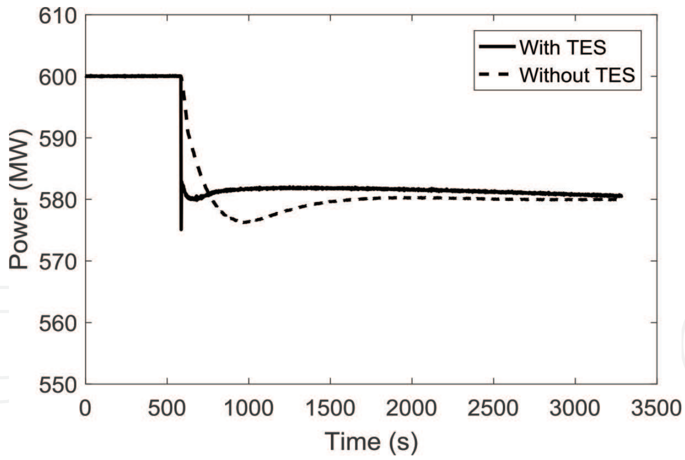

Figure 12. Off-peak period.

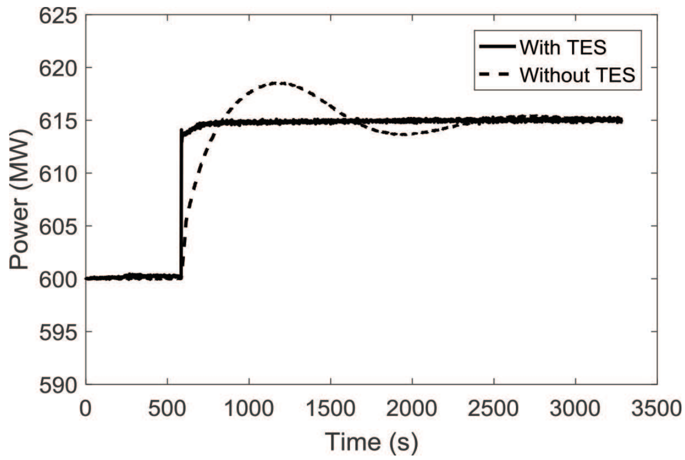

Figure 13. Peak period.

5. Conclusion

This chapter describes the simulation study of TES integration into a supercritical coal-fired power plant for efficient and flexible plant operation. Three TES charging strategies, and two TES discharging strategies were investigated. The simulation results show that it is feasible to extract thermal energy from the water-steam cycle for TES charging during the off-peak time period and to discharge the stored thermal energy back to the power generation process to water steam loop during the peak demand period to boost the power generation. According to the results, following conclusions can be drawn:

1. The flexibility of a supercritical coal-fired power plant can be improved with the TES integration.

2. For the TES charging process, the amount of the steam extraction needs to be restricted to a feasible range in order to maintain a stable power output.

3. For the first TES discharging strategy, the maximum mass flow rate of generated steam is 72.6 kg/s, and the corresponding overall output power is 644.4 MW.
4. For the second TES discharging strategy, the maximum output power is 634 MW.
5. With the TES integration, the supercritical coal-fired power plant presents faster dynamic responses to the load demand changes.

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