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An Optimization Method of Steam Turbine Load Resilient Adjustment by Characterizing Dynamic Changes in Superheated Steam Energy

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Abstract: Improving the dynamic regulation ability of thermal power units is effective for realizing flexible scheduling in modern power systems. At present, the unit regulation capacity is usually reflected by the load adjustment of the main steam pressure and flow tracking ability, through the calculation of the given and real-time deviation to complete the load, and by pressure adjustment. However, although the calculation involved in this method is easy and the results are intuitive, overshoot and lag can easily occur. The main reason for this is that the process from boiler combustion to turbine works has strong hysteresis and inertia, and the feedback signal of the pressure and flow rate cannot dynamically reflect the change in boiler combustion and steam energy. According to the heat transfer process of the unit, the main steam temperature can directly reflect the energy transfer in the furnace combustion process and then reflect the changing trend of steam energy. Analyzing the changing characteristics of the temperature, pressure, and flow of superheated steam under rapid load regulations makes it possible to calculate the instantaneous energy storage value of the main steam before the regulating valve, and this value was inserted into the coordinate system as a new feedforward signal. Finally, a simulation model was established by using the actual running data of the unit. A simulation experiment under variable working conditions demonstrated that this method could improve the dynamic adjustment of the unit to load and pressure and help the power grid absorb renewable energy.

Keywords: steam turbine; resilient adjustment; superheated steam energy; feedforward control; modeling and simulation

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1. Introduction

In 2015, at least 55 countries and regions under the United Nations Framework Convention on Climate Change jointly formulated the Paris Agreement, committing to controlling the increase in the global average temperature to within 2 °C compared with the preindustrial period and striving to limit the increase in temperature to within 1.5 °C. On this basis, China has formulated clearer environmental protection goals: "carbon neutralization and carbon emissions peak". The energy structure of the country is continuously transforming to "green" low-carbon. As a representative example of renewable energy at a high level in the grid, wind power is one of the best examples in terms of randomness and volatility; of course, solar power also has similar characteristics. In recent years, wind and solar power installations and generation have increased annually, as shown in Figure 1. To operate the power grid safely and stably, the elastic adjustment ability of the power grid should be greatly improved. In view of China's energy structure with rich coal and little oil, coal-fired units are still the main source of the power grid, so improving the load regulation capacity of thermal power units is essential to utilize renewable energy sources [1,2].

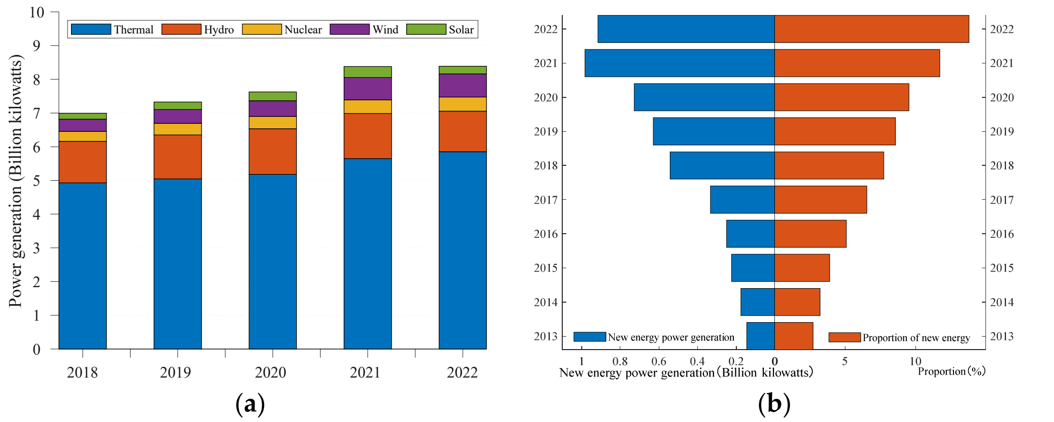

Figure 1. Development trend chart of new energy (wind power, solar energy): (**a**) Comparison of various types of power generation in China in the past five years and (**b**) New energy power generation, represented by wind power and solar energy, in China over the past decade and its proportion.

To solve the problems of randomness and the fluctuation of new energy in the power supply system, higher demands have been put forward for the load regulation capacity of thermal power units [3]. Improving the load regulation speed of thermal power units is an important topic. Given this goal, there are three main research directions. The first is to increase the performance and adaptive ability of the controller so that, when the unit is quickly adjusted, the controller can quickly track and adjust [4,5]. Typical methods for improving controllers include the fuzzy proportional–integral–derivative (PID) control, neural-network PID control, and a series of algorithms with adaptive tuning characteristics [6–9]. The second is to continuously enhance the research on institutional mechanisms. Based on the original institutional and numerical modeling, new data-processing methods have been used to establish more accurate models, such as neural-network models and data fusion models [10–12]. Third, new coordinated control schemes have been designed. This type of optimization is mainly based on a direct and indirect energy balance to optimize the control structure, such as feedforward feedback, decoupling control, and status feedback control, which can reduce the impact of furnace-side delay and make the coordination between the turbine and the boiler smoother [13–16]. The most important signals on which these methods are based are the vapor pressure and load signals, which can be obtained through operation or structural change in order to further optimize the performance of the boiler–turbine coordination control system [17,18].

The above methods have been widely used in actual units, greatly improving their rapid load adjustment capability. However, no in-depth research on the superheated steam section in front of regulating valves has involved the optimization of control algorithms, model construction, etc. In the existing control strategy optimization, the load is often directly fed back, the primary steam flow is associated with the adjustment of the load deviation, and the steam flow is used as a reference for the adjustment of the fuel-to-water ratio. Because the main value of the superheated steam in front of the regulating valves is to conduct work, the conventional flow signal cannot accurately reflect the adjustment ability of the steam. The fluctuation in the steam temperature and pressure affect the steam fluid greatly, reducing the accuracy of the load adjustment. However, in the current model construction method, the superheated steam in front of the regulating valves was not analyzed from the perspective of energy change, causing the algorithmic research mentioned previously to ignore the dynamic change in the superheated steam state in front of the turbine during the load change process.

The main goal of this study was to increase the regulatory flexibility of thermal power units. To reduce the hysteresis in the thermal power unit peak-shaving process, the change in the main steam temperature parameters is taken to be a characteristic response quantity of boiler combustion during dynamic adjustment. Combining the main steam pressure and temperature, the feedforward signal is refitted. In previous studies, many researchers have only used a unit load and pressure as the basic variables for feedforward and feedback in coordinated system control, ignoring temperature changes, making it impossible to perceive the operating state of the boiler quickly and directly. This results in certain limitations and reduces regulatory inertia. The biggest innovation in this study compared with the traditional optimization method is that the feedforward signal incorporated temperature values, which made it possible to sense the combustion changes in the boiler better and more in advance compared with using load and pressure feedback, thereby reducing the regulation hysteresis.

A method of optimizing steam turbine load resilience adjustment by characterizing the dynamic change in the superheated steam energy is presented in this article. The article is organized as follows. In Section 2, the energy storage and coordination control system of the thermal power unit are theoretically analyzed, followed in Section 3 by a data calculation method for the effective energy of superheated steam before the steam turbine. Section 4 discusses data processing and the analysis results in relation to Section 3. In Section 5, based on the results of Section 4, a control optimization method considering the effective energy feedforward signal of superheated steam is proposed, and a modeling simulation analysis is provided. In the simulation experiment, the given input value of the load with a large change in the model was assumed to be the command of the power grid to flexibly dispatch a thermal power unit when the actual load of a wind farm changed. Therefore, the simulation experiment was used to verify that the load elasticity regulation of thermal power units could smooth the adverse interference and influence of the uncertainty and variability of renewable energy generation on the power frequency balance of the grid.

2. Theoretical Analysis of Coordinated Control and Unit Energy Storage

The essential problem of a control system is to maintain the energy balance of the unit. The boiler is mainly responsible for converting the chemical energy of coal into the internal energy of water and steam, while the turbine is responsible for converting the internal energy of steam into mechanical energy, and the generator receives the kinetic energy to output electric energy. The traditional calculation of the steam turbine work capacity is based on the energy signal equivalence. The so-called "energy signal equivalence" means that the electric power expressed by the load signal is the signal measuring the energy output, and the steam flow is the energy input signal for work. The dynamic balance between the two is the ultimate objective of the control system. However, in the unit operation process, the energy input based on the steam flow signal is too ideal. The premise is that the steam temperature and steam pressure under each working condition are matched with the current load. Obviously, this energy signal can only represent the energy input situation when the load is stable and cannot always reflect the energy input situation in a large dynamic adjustment. It is especially difficult to ensure the performance of the control system when the units generally encounter a large amplitude and high-frequency peak shaving. As a result, taking greater advantage of the energy storage of the unit is a more viable optimization route for improving the speed of load regulation in the control system.

Based on the above background, in the current regulation optimization of thermal power units, the theory of energy storage was extensively studied. Because the large delay and inertia of thermal power units are mainly on the boiler side, research on the energy storage of saturated water and saturated steam on the boiler side is more practical, and the result is conducive to research on the optimization of the later control system. First, according to the characteristics of energy transmission in different stages, the energy storage of saturated water and steam is divided into basic and instantaneous. The relationship between the two is that the former determines the continuity of instantaneous energy storage, and the latter determines the rapidity of basic energy storage. In the following, the causes are analyzed.

(1) In the existing control system, the coordination mode based on BF (boiler following) can quickly track the load deviation, which is mainly reflected in the adjustment of

the steam pressure during the turbine regulation process. The change in the working medium in this section is instantaneous energy storage in the superheated steam section. In the logic design, the change in pressure can be directly linked to the adjustment in the fuel system. The most intuitive phenomenon of the adjustment in the air and flue gas system is the heat absorption change in the drum and water wall. The change in the working medium in this section pertains to basic energy storage. This is the reason why instantaneous energy storage can increase basic energy storage.

(2) Similar to the analysis in (1), when no load adjustment is performed, the function of the drum and water wall as the basic energy storage system is to convert the undersaturated water into saturated water and then into saturated steam, finally entering the superheated steam system. Therefore, when the system enters the adjustment stage, the superheated steam, as well as the instantaneous energy, can realize the function of instantaneous regulation, and the basic energy storage value can determine whether there is a sudden pressure drop/rise, or even an overpressure/cross pressure during the adjustment process. Therefore, the energy storage system of the water wall and drum is the basic energy storage system that determines the instantaneous regulation capability of the superheated steam.

(3) When energy is transferred from the boiler to the turbine, the main steam temperature is more sensitive to the combustion of the boiler and can quickly react to the input and disturbance of fuel. The change in the steam flow mainly reflects the evaporation capacity of the boiler, which is greatly affected by the load setting. The change in steam pressure (taking the boiler turbine as an example) is greatly affected by the control valve, which also reflects the ability of the unit to adjust the load quickly.

According to the above analysis, in this study, the main steam temperature, pressure, and flow were taken as the basic signals to obtain the energy signals that could characterize the changes in steam energy and dynamically reflect the changes in energy transmission from the boiler to the turbine. Finally, this signal was applied to the optimization of a traditional control system to improve the stability and rapidity of the load and pressure output when the unit energy was dynamically adjusted.

3. Calculation of Superheated Steam Energy Signal

According to the above analysis, a method for the quantitative calculation of superheated steam energy is proposed. The basic idea is as follows:

As shown in Figure 2, the field data for different operating conditions, including load value, main steam temperature, pressure, and flow rate, were collected first. Then, the enthalpy, entropy, and effective energy of superheated steam in front of the regulating valves were converted into an equivalent load signal, which was then added to the coordination system as a feedforward signal to complete the control optimization of the system.

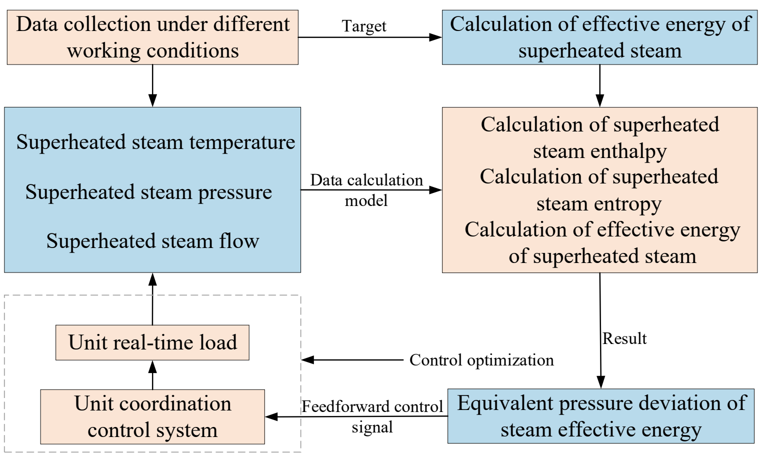

Figure 2. Data processing and implementation scheme.

To facilitate the understanding of the whole energy calculation process, the meanings of variables involved in it are now explained, as shown in Table 1 below:

(1) The difference in effective energy between the two load points was calculated, the difference between the two loads was converted into energy, and the energy difference between the two load points was obtained. The calculation is as follows:

Table 1. Names and meanings of the variables.

Variable Name	Meaning of Variables
ΔN	Load difference
N_i/N_s	Unit load at time i/s
$\Delta Q(N_i,N_s)$	Unit energy change as load changes from Ni to N_s
$\Delta Q_N(N_i,N_s)$	The energy required by the actual load change in the unit when the load changes from N_i to N_s
$\Delta Q_{SS}(N_i,N_s)$	The energy required to change the steam state of the unit when the load changes from N_i to N_s
ΔN_{ss}	The equivalent load value of the energy required to change the steam state
P/T/t	Pressure/Pressure and Kelvin temperature/Celsius
q_i/q_s	Steam flow rate at time i/s
H_0/H_i	The initial enthalpy and the instantaneous enthalpy
S_0/S_i	The initial entropy and the instantaneous entropy
E_{si} (N_i, P_i)	The workable energy of steam at stable load N_i and pressure P_i
Q_{ssi}	Steam working energy, combined with the flow rate q_i of load point N_i

$$\Delta Q(N_i, N_s) = \Delta Q_N(N_i, N_s) + \Delta Q_{SS}(N_i, N_s) \tag{1}$$

where $\Delta Q(N_i,N_s)$ is the energy required for a load increase from N_i to N_s, and $\Delta Q_N(N_i,N_s)$ is the change in the superheated steam energy at the front of the turbine of $\Delta Q_{SS}(N_i,N_s)$. The equivalent load value ΔN_{ss} obtained from the main steam energy change $\Delta Q_{SS}(N_i,N_s)$ according to Equation (1) is used to correct the load deviation ΔN.

(2) The equivalent load deviation under a different regulation amplitude corresponds to a specific load point based on the actual data of the unit.

According to the steam and water characteristics of a 300-MW drum boiler, the superheated steam energy storage in front of the turbine, and the two assessment rules, the equivalent load deviation under different load adjustment ranges can be obtained.

When the load changes from N_i to N_s, the main steam flow changes from q_i to q_s, and the change is:

$$\Delta q = q_s - q_i \tag{2}$$

To calculate the change in the steam energy, it can be assumed that E_{si} (N_i, P_i), namely, the effective energy of superheated steam, can characterize the energy per kilogram of steam in front of the turbine. The steam energy can be calculated as follows:

$$E_{si}(N_i, P_i) = (H_i - H_0) - T_0(S_i - S_0) \tag{3}$$

where H_0 and H_x represent the enthalpy in the base state and the enthalpy in the initial state, respectively (kJ/kg), S_0 and S_x represent the entropy of the base state and the entropy of the initial state (kJ/(kg·K)), and T_0 is the initial temperature (K). The initial enthalpy value takes the enthalpy value of steam (at 450 °C, 10 MPa), and the entropy value retains the initial value, so H_0 = 192.4346 kJ/(kg·K) and S_0 = 0.3806 kJ/(kg·K) can be calculated.

The above enthalpy value can be calculated by the method of steam parameters—that is, when the pressure p and temperature t, which are easy to measure, are selected as independent variables, and the result is Equation (6). The calculation method can be found elsewhere [19,20].

$$H = f_0(p, t) \tag{4}$$

Similarly, the entropy calculation model used in the previous work [21] for the calculation of the entropy under the above temperature and pressure is given as follows:

$$s = ((0.40451 \ln \frac{T+273}{273} + 0.00013 \times T - 0.110117 \ln(\frac{P}{0.101325} + 1) \\ + 1.6273 - \frac{0.8875561 \times (\frac{P}{0.101325}+1)+34.800775}{(\frac{T+273}{100})^4}))/0.239 \quad (5)$$

where T and P represent the temperature (K) and standard atmospheric pressure (atm), respectively, and S is in kJ/(kg·K). The conversion relationship is as follows:

$$1 \times P = 101.325kPa \quad (6)$$

The enthalpy value of superheated water steam can be calculated by referring to the method that calculates the enthalpy value by dividing the areas and sections adopted in a previous study [22] as follows:

$$H = (782.6 + 0.627 \times (T - 450)^{0.9984} - \frac{0.316 \times ((\frac{P}{0.101325} + 1) - 80)^{1.042}}{0.0059T - 1.655})/0.239 \quad (7)$$

The above steam pressure range is 80–180 times the absolute atmospheric pressure, the temperature range is 450–570 °C, and the unit of H is kJ/kg. Equation (3) E_{si} (N_i, P_i) can be calculated from Equations (5)–(8). Combining the flow rate qi of the load point Ni, the steam working energy Q_{ssi} can be obtained. With the same load point Ns, the following calculation data model for the instantaneous energy storage of superheated steam in front of the regulating valves could be obtained by combining the above formula:

$$Q_{ssi} = q_i \cdot E_{si}(N_i, P_i) \quad (8)$$

Based on Equation (3), a ΔQ calculation model that can be used to calculate the instantaneous energy storage change in superheated steam between two points ΔQ_{SS} (N_i, N_s) is:

$$\Delta Q_{ss}(N_i, N_s) = Q_{sss} - Q_{ssi} \quad (9)$$

This instantaneous energy storage deviation was converted into the equivalent hourly power of the unit (equivalent load deviation).

$$\Delta N_{ss} = \Delta Q_{ss}(N_i, N_s)/q_0 \quad (10)$$

where q_0 = 3.6 × 10^6 J, and ΔN_{ss} is the instantaneous equivalent load deviation.

4. Data Processing and Calculation Result Analysis

To verify the quantitative value of the instantaneous energy signal of superheated steam further, the parameters of the two operating states of the unit were processed and analyzed. First, the output value of the energy signal and the load change during the load change process were compared. Then, the energy signal value and the changing energy signal value under a specific load condition were compared.

4.1. Calculation and Analysis of Energy Signal under Continuous Load Change

Based on the above-related theories in Section 3, the dynamic energy required by the superheated steam in front of the regulating valves and the relevant calculation results are shown in Table 2 below:

Table 2. Change trend in the effective energy of superheated steam in front of the regulating valves during unit loading.

Load	Main Steam Flow (t/h)	Main Steam Temperature (°C)	Main Steam Pressure (MPa)	Steam Enthalpy (kJ/kg)	Steam Entropy (kJ/kg · K))	Effective Energy (kJ/kg)	Total Energy (kJ)	Equivalent Load (MW)
264.13	826.5	54h0.069	16.368	3.34×10^3	6.715	19.273	1.59×10^7	4.425
266.09	852.9	537.464	15.721	3.34×10^3	6.722	21.772	1.85×10^7	5.159
268.11	908.6	534.766	15.521	3.33×10^3	6.720	14.368	1.30×10^7	3.626
270.48	924.1	534.837	15.544	3.33×10^3	6.720	14.175	1.31×10^7	3.639
271.27	930.7	535.093	15.496	3.34×10^3	6.722	16.340	1.52×10^7	4.225
274.29	931.7	535.032	15.491	3.33×10^3	6.722	16.184	1.50×10^7	4.189
276.04	935.9	535.131	15.555	3.33×10^3	6.720	15.217	1.42×10^7	3.956
278.00	859.8	539.395	16.112	3.34×10^3	6.718	21.782	2.03×10^7	5.663
280.06	940.6	536.227	15.647	3.34×10^3	6.721	17.990	1.69×10^7	4.700
282.05	945.1	537.164	15.738	3.34×10^3	6.721	20.098	1.89×10^7	5.276
284.42	936.3	537.473	15.832	3.34×10^3	6.720	19.413	1.81×10^7	5.050

In Figure 3, the parameter change trend shows that the changing trend in the main steam pressure and flow was positively related to the load adjustment, and the main steam temperature increased in this area. The field data in Table 2 the existing basic theory is confirmed; that is, the adjustment of load and pressure is closely related to the change in the superheated steam parameters. In particular, the main steam pressure and flow can describe the load output of the unit to a certain extent. However, by referring to the load and pressure curve in the initial stage (data points 0–30 s) and the load and main steam flow curve at the intermediate stage (data points 30–50 s) during the load adjustment process, a single steam parameter in a certain area cannot effectively describe the load output of the unit. However, the external load command adjustment (load setpoint 37 data point) did not rapidly increase the speed of the load adjustment. The above mismatch directly led to the inconsistency of load deviation and pressure deviation changes, which caused a certain range of disturbances in the fuel and regulating valve action. Therefore, it is important to find variables that can directly describe the load change state.

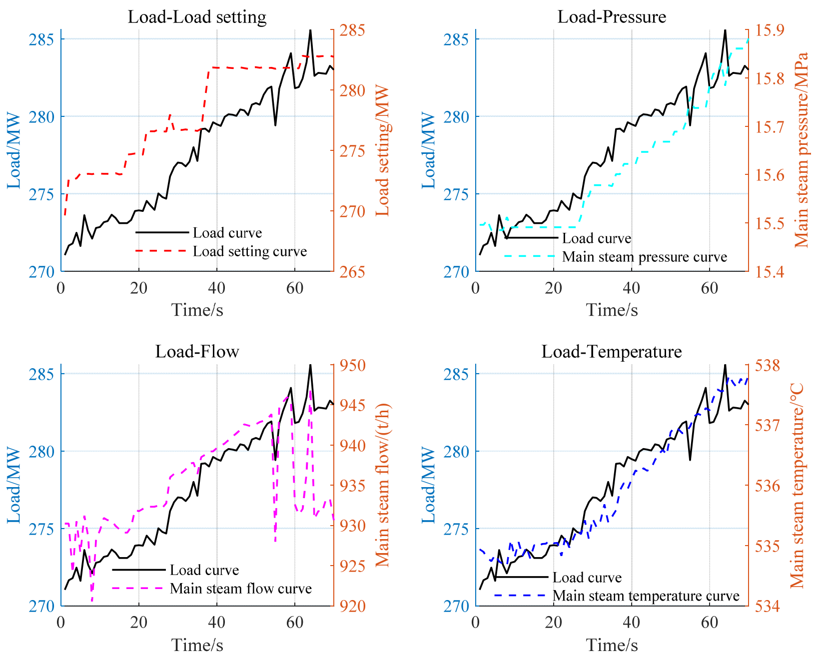

Figure 3. Variation between load and main steam parameters during loading.

In the above data analysis, the second part introduces the calculation method of the steam energy value, and the energy value in Table 2 could be obtained. Its tracking trend with load is shown in Figure 3.

Comparing the curves in Figure 4 reveals that the output data of the energy model can more effectively track the load change in the adjustment process compared with the single main steam parameter. To further compare the description effect of the energy output of the model with the single steam parameter, a deviation comparison was made, and is shown in Figure 5.

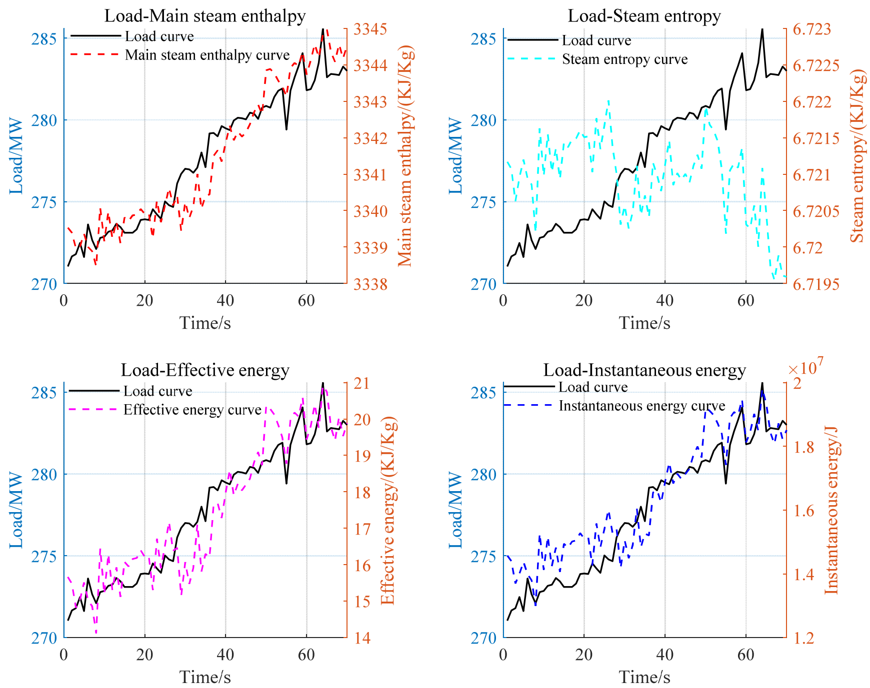

Figure 4. Changes in load and steam energy parameters during load application.

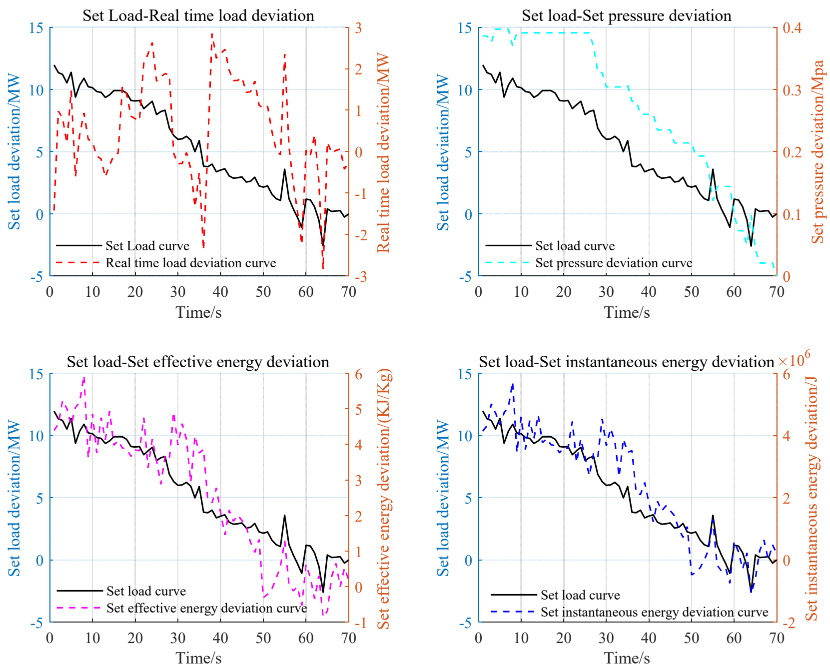

Figure 5. Pressure energy deviation response caused by load tracking during load application.

The curve under the dynamic load change shown in Figure 6 reveals that, for the disturbance of the load setting, the fuel regulation was more sensitive with the pressure as the feedforward, resulting in large fluctuations, and the steam energy was the feedforward signal, which not only reflected the load adjustment state of the unit but also reduced any disturbance to the boiler combustion. While a simple load deviation (black curve) cannot truly reflect the real-time load deviation (red curve), the available energy deviation of steam (pink curve) can reflect the real-time load deviation value in advance.

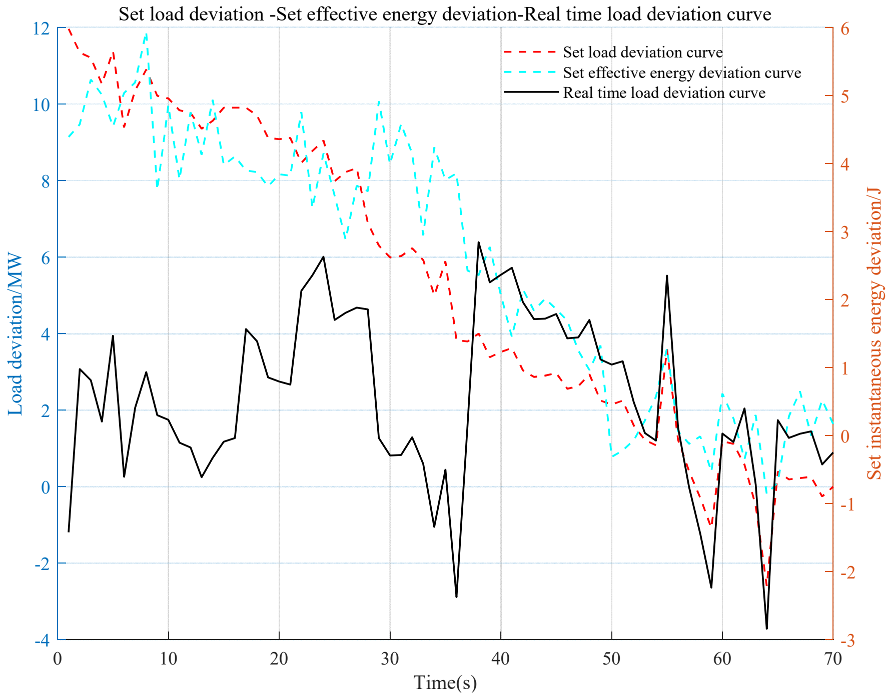

Figure 6. Comparison of real-time load deviation between load setting deviation and the available steam energy deviation.

The conclusion that can be drawn from the above analysis is that the instantaneous energy of superheated steam can more effectively describe the load output state of the unit.

4.2. Comparison of Superheated Steam Energy Model Output under Stable State and Load Change State under the Same Load Output of the Unit

Taking a 220.167 MW load stable operation state of the unit as the target load, the control decision of the unit when 200 MW is adjusted to 220.167 MW under different conditions was analyzed. Under this target value, the main steam flow was 780.93 t/h, the temperature was 537.387 °C, and the steam pressure was 14.466 MPa.

To compare further the energy deviation during load adjustment and the single superheated steam parameter deviation, the instantaneous energy of the 220.167-MW load was calculated from Table 3 using the instantaneous energy model of superheated steam, and the first column of the equivalent load value in Table 4 was also calculated. The difference value of the statistical energy data in Table 3 was taken. The second, third, and fourth columns of Table 4 can be obtained by comparing the difference obtained with the parameters of superheated steam under the target load of 220.167 MW. According to each deviation, the corresponding adjustment strategy was obtained, as shown in Table 4. Here, each row of Table 4 corresponds to a row in Table 3, which is the same working condition.

Table 3. Calculation of the instantaneous energy of superheated steam in front of the unit under different adjustment conditions under the same load output of the unit.

Unit Status	Actual Power (MW)	Main Steam Flow (t/h)	Main Steam Temperature (°C)	Main Steam Pressure (MPa)	Instantaneous Energy (KJ/KG)
Steady load	200.748	679.23	536.756	14.274	617,946,898.8
Load reduction	200.713	715.93	537.964	14.918	652,071,612.4
Stable load reduced to 200	200.748	673.88	538.918	15.393	614,330,510.4
Load up	200.713	726.51	540.813	14.314	667,724,775.8

Table 4. Comparison between instantaneous energy deviation and single steam parameter deviation.

200 MW to 220 Equivalent Load Deviation (MW)	Pressure Deviation (MPa)	Load Display Deviation (MW)	Flow Self Deviation (t/h)	Corresponding Adjustment Strategy
19.934	0.613	19.419	keep	Keep the pressure and feed-back the load deviation
10.454	0.735	19.454	36.7	Maintain pressure and correct load deviation
20.938	−0.138	19.419	−5.354	Reduce the pressure and fine tune the load deviation
6.106	1.217	19.454	47.283	Increase pressure and correct load deviation

A comparison of the calculation results reveals that when the instantaneous energy signal output of the superheated steam differs from the target load, the energy storage signal of the equivalent load deviation can be obtained. When the real load deviation is almost unchanged (see the third column of Table 4), this signal truly reflects the instantaneous energy storage state of superheated steam in front of the turbine, which can also be used to predict the energy storage change in the superheated steam in front of the turbine in advance. On this basis, combined with the pressure deviation and flow deviation of superheated steam, the existing unit control model was optimized by using the instantaneous energy signal of superheated steam in front of the regulating valves as feedback.

5. Unit Model Optimization and Field Data Simulation Comparison

In the following, the real-time superheated main steam temperature and flow value were introduced into the traditional model in combination with the field data and the main steam pressure value. Through the above Section 3 energy calculation method, the instantaneous energy signal of the superheated steam was calculated. Then, this signal was integrated into the existing model to correct the pressure deviation signal in real-time. This method can reduce pressure fluctuation and overshoot and improve load control accuracy. Against this background, the feasibility of the above theory was verified by applying a large-scale load change instruction input model. Thus, the simulation comparison curve was obtained. The principle is shown in Figure 7.

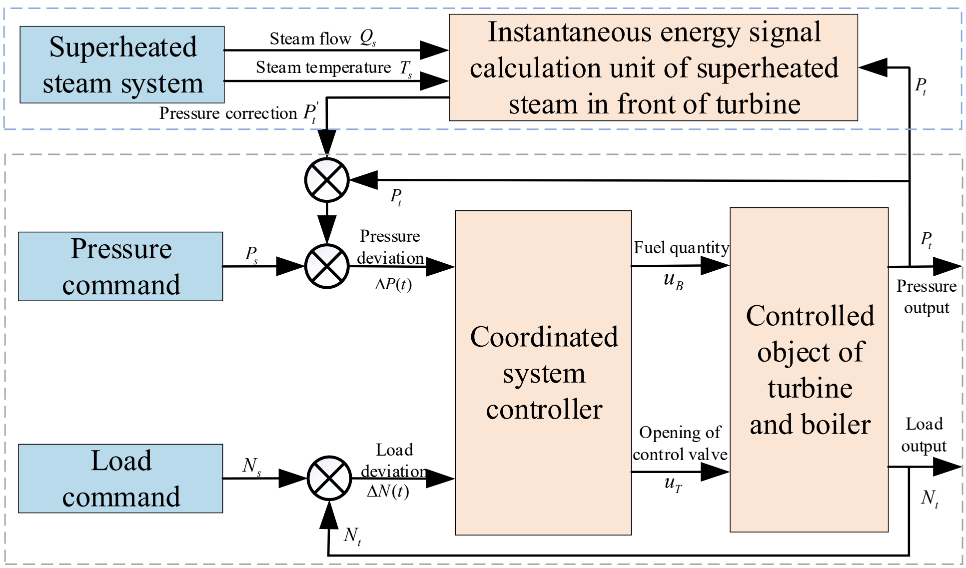

Figure 7. Coordination and optimization based on correction of superheated steam energy storage in front of turbine.

Because the data used in the above analysis were from a 330-MW unit in a thermal power plant, the following modeling takes this unit as the object and imports real-time data into the model. According to the field data, the parameters of the model can be calculated by using the closed-loop identification method. The following relationship was obtained from previous work [23,24]:

$$K_f dr_b/dt = -r_b + e^{-\tau s} u_B \tag{11}$$

$$C_b dp_b/d_t = -K_3 p_t \mu_t + K_1 r_b \tag{12}$$

$$K_t dN/dt = -N + K_3 p_t \mu_t \tag{13}$$

$$p_t = p_b - K_2 (K_1 r_b)^{1.3} \tag{14}$$

where K_1, K_2, and K_3 are the fuel gain, superheater drag coefficient, and turbine gain, respectively; τ, T_{f}, C_b, and T_t are the delay time of the coal mill, the dynamic time of the coal mill, the boiler's heat storage coefficient, and the dynamic time of the steam turbine; r_b is the amount of pulverized coal output by the mill; pb is the rated drum pressure; p_t is the regulation stage pressure; μ_t is the steam turbine regulating the valve opening; and N is the unit output load. The above formula, Equation (11) describes the inertia of pulverizing, Equation (12) and describes the energy balance of the boiler while Equation (13) describes the energy balance equation of the steam turbine and Equation (14) describes the differential pressure characteristics of a superheater. Based on the above model, the following simulation was carried out.

Two sets of curves were obtained. One is the load and pressure model response curve without superheated steam energy compensation in front of the regulating valves. The other is the model response curve after introducing the instantaneous energy signal.

An analysis of the curves in Figure 8 shows that when the unit coordination system was not compensated for and corrected, the general model simulation curve (red curve) had a large deviation in the adjustment process, while the actual unit adjustment curve (blue curve) also had a large deviation in the adjustment process (such as in the blue circle). The final stable value in Figure 8, no matter the field load response curve or the load response curve of the simulation model, had a certain amount of deviation from the real load setting value; that is, the load setting value was not well tracked in the final stable period.

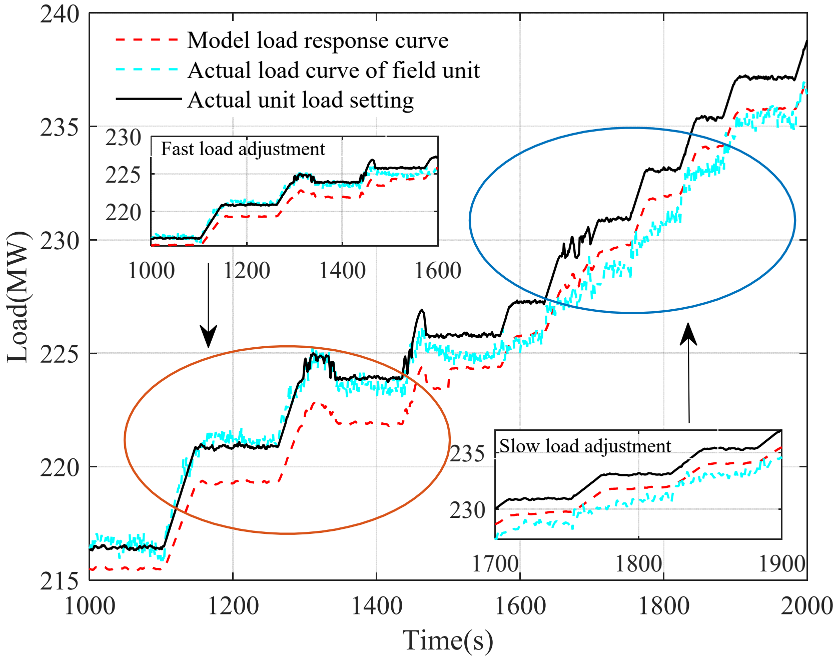

Figure 8. Load response curve under traditional modeling mode.

Similar to Figure 9, the load response curve, when the unit coordination system was not compensated for and corrected, no matter the real unit response curve or the modeling and simulation curve, still showed a large pressure regulation deviation, which reached 0.8 MPa. Such a large deviation reflects that there was a certain lag and delay in the pulling back of pressure in the unit coordination system during rapid load mediation. This affected the continuous load adjustment capacity of the unit and reduced the performance of the primary frequency modulation.

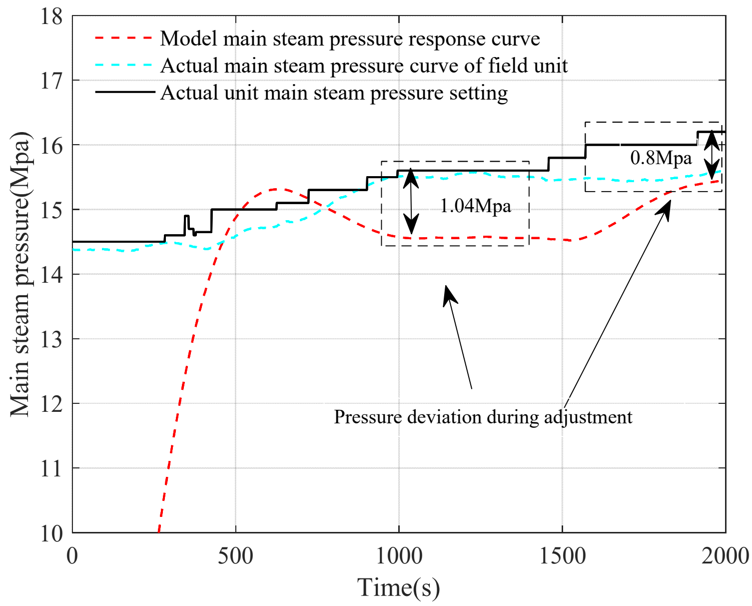

Figure 9. Main steam pressure response curve under traditional modeling mode.

According to the simulation model response results, the superheated steam energy signal in front of the turbine was introduced into the model, and the same actual load and pressure setting values as in the above model were used to compare and verify the optimized load and pressure response curves, as shown in Figures 10 and 11.

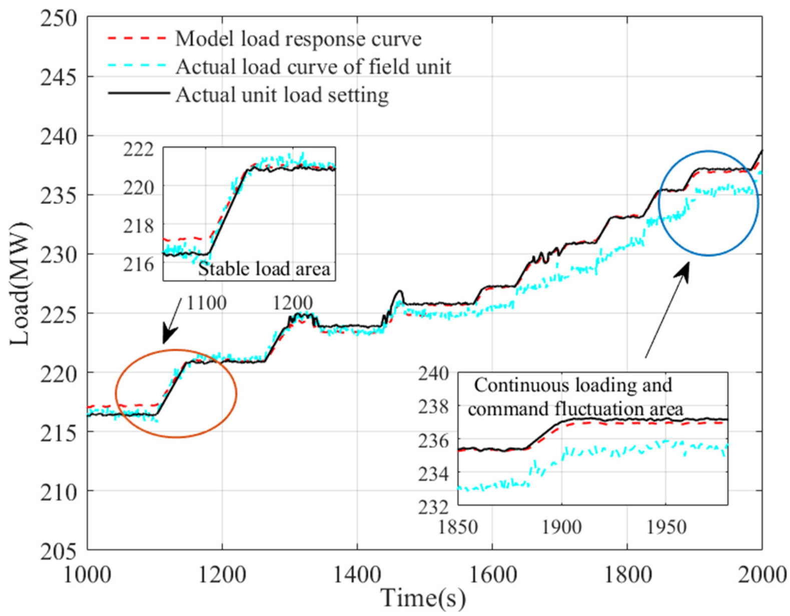

Figure 10. Load response curve after model optimization and compensation.

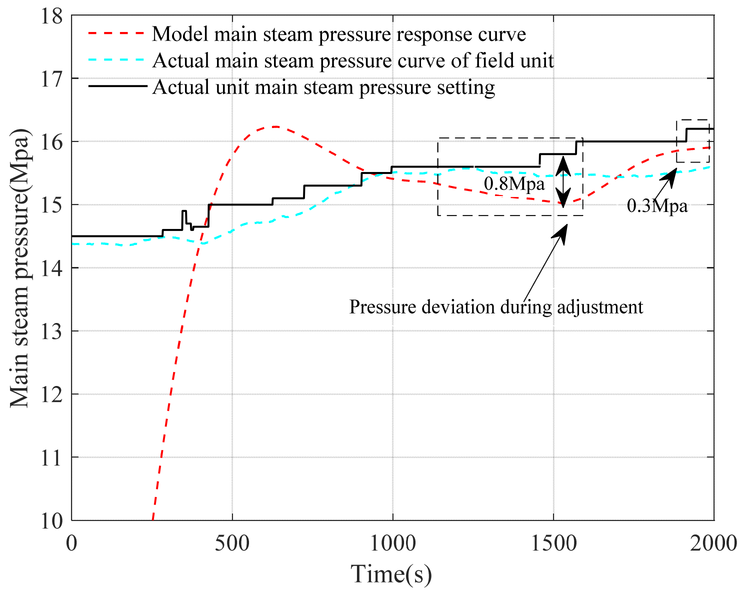

Figure 11. Pressure response curve after model optimization and compensation.

The red curve in Figure 10 is the model load response curve, and the green curve is the actual unit response curve after the instantaneous energy signal compensation of the superheated steam in front of the machine was adopted. After the feedforward compensation was added to the model, the load instruction could be tracked in time for the entire loading interval, as well as the load regulation of the coordinated system, and the final deviation was less than the actual unit deviation.

To avoid the influences of different controllers on the simulation results, the simulation experiments were carried out using the same controller. Comparing the results in Figure 11 revealed that, after the pre-engine superheated steam energy signal compensation, there was a certain overshoot (400–900 s time interval) in the initial stage. However, in the entire loading process, the pressure response deviation of the model after feedforward compensation was improved. This result (red dashed line) is not only better than that of the actual unit (blue dashed line), but it also significantly reduces the pressure deviation of the entire process compared with the original coordination model (no feedforward signal is added in Figure 9). The final pressure deviation was reduced from 0.8 MPa (Figure 9) to 0.3 MPa (Figure 11), which facilitated the continuous load and pressure adjustment and improved the frequency modulation performance of the unit.

6. Conclusions

Taking thermal power units as the research object, an optimization strategy that can improve the control flexibility of the units was developed in view of the related problems caused by renewable energy at a high level in the grid. According to previous research results, improving the flexibility of the load regulation of thermal power units can improve the absorption of new energy into the grid [25,26]. The biggest innovation of this study is the feedforward signal selection. By collecting the superheated-steam-related parameters of the thermal power units in the field load regulation process, the change characteristics of steam under the regulating-valve-related parameters in each load regulation process could be compared and analyzed. A method for calculating instantaneous energy storage using the traditional superheated steam parameters was devised, and the instantaneous energy storage was converted into an equivalent load signal, which was introduced into the unit control system. The effectiveness of this optimization method was proved by comparing the simulation model curve with the actual unit running curve, which provided a reference for the accurate regulation of unit load. The conclusions of this study and its prospects are as follows.

(1) A large number of real-world operation data on thermal power units were collected. Classification processing and analysis revealed that the energy variation in the superheated steam before the valve was regulated directly related to its temperature, pressure, and flow value. On this basis, the effective energy of superheated steam before the regulating valve was calculated. This energy indicates the size of the superheated steam's instantaneous energy storage, which also determines the load regulation capacity of the unit.
(2) Compared with the traditional control strategy optimization method that only uses load and pressure signals, this method of calculating the instantaneous storage energy of superheated steam integrates the change characteristics of the main steam temperature, which can better reflect the energy transfer in the furnace combustion process. This was added to the coordination system as a feedforward signal to improve the furnace-side adjustment speed, which could also be used to correct the deviation of the load and pressure and reduce the overshoot problem caused by the rapid adjustment of the load. The instantaneous maximum pressure deviation was reduced by 60%, and the instantaneous maximum load deviation was reduced by 90%.
(3) This method makes full use of the field unit operating data, reoptimizes the simulation model, and improves the accuracy of the simulation experiment. Large load change signals were added to the simulation model. The comparison between the simulation results and the actual unit response curve verified the effectiveness of the proposed compensation method.
(4) The energy calculation method, when proposed, could be gradually refined. Through the collection and processing of big data, it can be applied to 600-MW and 1000-MW steam turbine units, especially for coal-fired units with a strong hysteresis, which demonstrates its application value.

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References

1. Yang, L.; Xing, Z.; Peng, G. Research on heat and electricity coordinated dispatch model for better integration of wind power based on electric boiler with thermal storage. *IET Gener. Transm. Distrib.* **2018**, *12*, 3736–3743. [CrossRef]
2. Díaz-González, F.; Sumper, A.; Gomis-Bellmunt, O.; Villafáfila-Robles, R. A review of energy storage technologies for wind power applications. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2154–2171. [CrossRef]
3. Zhu, M.; Li, J. Integrated dispatch for combined heat and power with thermal energy storage considering heat transfer delay. *Energy* **2022**, *244*, 123230. [CrossRef]
4. Fan, H.; Zhang, Y.F.; Su, Z.G.; Wang, B. A dynamic mathematical model of an ultra-supercritical coal fired once-through boiler-turbine unit. *Appl. Energy* **2017**, *189*, 654–666. [CrossRef]
5. Ma, L.; Lee, K.Y.; Wang, Z. Intelligent coordinated controller design for a 600 MW supercritical boiler unit based on expanded-structure neural network inverse models. *Control Eng. Pract.* **2016**, *53*, 194–201. [CrossRef]
6. Chandrasekharan, S.; Panda, R.C.; Natrajan, S.B. Dynamic analysis of the boiler drum of a coal-fired thermal power plant. *Simulation* **2017**, *93*, 995–1010. [CrossRef]
7. Huang, C.; Sheng, X. Data-driven model identification of boiler-turbine coupled process in 1000 MW ultra-supercritical unit by improved bird swarm algorithm. *Energy* **2020**, *205*, 118009. [CrossRef]

8. Niu, Y.; Du, M.; Ge, W.; Luo, H.; Zhou, G. A dynamic nonlinear model for a once-through boiler-turbine unit in low load. *Appl. Therm. Eng.* **2019**, *161*, 113880. [CrossRef]
9. Hou, G.; Du, H.; Yang, Y.; Huang, C.; Zhang, J. Coordinated control system modelling of ultra-supercritical unit based on a new TS fuzzy structure. *ISA Trans.* **2018**, *74*, 120–133. [CrossRef]
10. Benalcazar, P. Sizing and optimizing the operation of thermal energy storage units in combined heat and power plants: An integrated modeling approach. *Energy Convers. Manag.* **2021**, *242*, 114255. [CrossRef]
11. Wang, Z.; Liu, M.; Yan, J. Flexibility and efficiency co-enhancement of thermal power plant by control strategy improvement considering time varying and detailed boiler heat storage characteristics. *Energy* **2021**, *232*, 121048. [CrossRef]
12. Liu, J.Z.; Yan, S.; Zeng, D.L.; Hu, Y.; Lv, Y. A dynamic model used for controller design of a coal fired once-through boiler-turbine unit. *Energy* **2015**, *93*, 2069–2078. [CrossRef]
13. Yang, S.; Wang, C.; Zhao, C.; Deng, K. Research on Feed-Forward PID Controller Based on Nonlinear Hammerstein Model for Electronic Throttle Control. In Proceedings of the 2013 International Conference on Control Engineering and Communication Technology, Washington, DC, USA, 7–9 December 2013; IEEE Computer Society: Washington, DC, USA, 2013; pp. 562–567.
14. Fan, H.; Su, Z.G.; Wang, P.H.; Lee, K.Y. A dynamic mathematical model for once-through boiler-turbine units with superheated steam temperature–ScienceDirect. *Appl. Therm. Eng.* **2020**, *170*, 114912. [CrossRef]
15. Zeng, D.; Gao, Y.; Hu, Y.; Liu, J. Optimization control for the coordinated system of an ultra-supercritical unit based on stair-like predictive control algorithm. *Control Eng. Pract.* **2019**, *82*, 185–200. [CrossRef]
16. Franco, A.; Diaz, A.R. The future challenges for clean coal technologies: Joining efficiency increase and pollutant emission control. *Energy* **2009**, *34*, 348–354. [CrossRef]
17. Huang, Y.; Cheng, Y.; Zhang, W. A feed-forward and feedback control scheme for boiler-turbine coordination control system. In Proceedings of the 2017 Chinese Automation Congress (CAC), Jinan, China, 20–22 October 2017; IEEE: New York, NY, USA, 2018; pp. 3860–3863. [CrossRef]
18. Wang, G.; Wu, J.; Ma, X. A nonlinear state-feedback state-feedforward tracking control strategy for a boiler-turbine unit. *Asian J. Control Affil. ACPA Asian Control Profr. Assoc.* **2020**, *22*, 2004–2016. [CrossRef]
19. Malhotra, A.; Panda, D.M.R. Thermo dynamic properties of superheated and supercritical steam. *Appl. Energy* **2001**, *68*, 387–393. [CrossRef]
20. Senegacnik, A.; Matija, T. Quick evaluation of the thermodynamic properties of water and steam. *Appl. Energy* **1994**, *49*, 369–378. [CrossRef]
21. Gareeva, D.T.; Lavrov, N.A. Entropy Production and Exergy Loss during Mixing of Gases. *Chem. Pet. Eng.* **2016**, *51*, 759–764. [CrossRef]
22. Wagner, W.; Cooper, J.R.; Dittmann, A.; Kijima, J.; Kretzschmar, H.J.; Kruse, A. The IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam. *J. Eng. Gas Turbines Power* **2000**, *122*, 150. [CrossRef]
23. Hou, G.; Gong, L.; Hu, B.; Huang, T.; Su, H.; Huang, C.; Zhou, G.; Wang, S. Flexibility oriented adaptive modeling of combined heat and power plant under various heat-power coupling conditions. *Energy* **2022**, *242*, 122529. [CrossRef]
24. Zhou, H.; Chen, C.; Lai, J.; Lu, X.; Deng, Q.; Gao, X.; Lei, Z. Affine nonlinear control for an ultra-supercritical coal fired once-through boiler-turbine unit. *Energy* **2018**, *153*, 638–649. [CrossRef]
25. Wang, J.J.; Zhang, S.; Huo, J.K.; Zhou, Y.; Li, L.; Han, T.Y. Dispatch optimization of thermal power unit flexibility transformation under the deep peak shaving demand based on invasive weed optimization. *J. Clean. Prod.* **2021**, *315*, 128047. [CrossRef]
26. Zeng, J.M.; Liu, L.D.; Liang, X.; Chen, S.H.; Yuan, J. Evaluating fuel consumption factor for energy conservation and carbon neutral on an industrial thermal power unit. *Energy* **2021**, *232*, 120887. [CrossRef]