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Compensation Design of Coordinated Control System for Supercritical Once-Through CHP Plants Based on Energy Analysis

TUOYU DENG[1], LIANG TIAN[1], CHENGXI ZHOU[2], XINPING LIU[1], AND WENLEI DOU[2]
[1]School of Control and Computer Engineering, North China Electric Power University, Baoding 071003, China
[2]State Grid Liaoning Electric Power Company Ltd., Shenyang 110006, China
Corresponding author: Tuoyu Deng (dty@ncepu.edu.cn)

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ABSTRACT To increase the flexibility of power generation, the supercritical once-through boiler combined heat and power (CHP) plant should improve its coordinated control system (CCS). The difficulty of CCS for supercritical once-through boiler unit is to determine the water-fuel ratio in the dynamic process. First, a CHP unit model is established and simplified into a three-input three-output object under pure condensing working conditions. Second, dynamic relative matrix gain method and simulation is used to analysis several once-through boiler coordinated control schemes commonly used in engineering in which the compensation link is designed on the basis of water-fuel ratio. Simulation results show that, the water following CCS scheme has better intermediate point temperature performance and worse throttle pressure performance than the fuel following CCS scheme. To improve pressure performance, the closed-loop characteristics of pressure response to fuel and feed water flow are analyzed and compared through wavelet analysis. Finally, a method for determining the inertia time constant in the dynamic compensation link by comparing the wavelet coefficients is proposed. Wavelet analysis show that the imbalance in the speed of energy changes to fuel and feed water flow is the essential cause of large fluctuations in intermediate point temperature and throttle pressure before turbine of the supercritical once-through boiler unit. Simulation results show that using the proposed dynamic compensation in water following CCS can effectively reduce fluctuations of the intermediate point temperature and fluctuations of throttle pressure before turbine when power load command changes.

INDEX TERMS Coal-fired power plant, once-through boiler, coordinated control system, water-fuel ratio, relative gain array method, wavelet analysis.

NOMENCLATURE

Variables

u_T	opening of regulating valve of high-pressure cylinder %
u_B	fuel flow t/h
u_W	feed water flow t/h
u_E	opening of regulating butterfly valve of heating extraction %
u_L	opening of low-pressure cylinder inlet valve %
p_t	throttle pressure before turbine MPa
N_E	power load MW
T_d	intermediate point temperature °C
h_d	specific enthalpy of intermediate point kJ/kg
p_e	heat extraction pressure MPa
r_B	boiler fuel flow rate kg/s
q_W	feed water flow of phase change section kg/s
p_b	pressure of steam water separator MPa
τ_f	delay time of the pulverizing process s
τ_d	delay time of the slightly superheated section s
T_{f1}, T_{f2}	inertial time constant of the pulverizing process s
C_m	heat storage coefficient of boiler metal MJ/MPa

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C_v	heat storage coefficient of steam-water system MJ/MPa
$\boldsymbol{G}$	non-singular square matrix
$\boldsymbol{I}$	identity matrix
i	output number of transform function
j	input number of transform function
t	time
s	complex variable
$G_{ij}(s)$	transform function between input j and output i
$C_{PID}(s)$	transform function of PID controller
$F_w(s)$	transform function of compensation link
$p_{t,sp}$	set point value of throttle pressure before turbine MPa
$N_{E,sp}$	set point value of power load MW
$T_{d,sp}$	set point value of intermediate point temperature °C

Abbreviations

CHP	combined heat and power
CCS	coordinated control system
PV	photovoltaics
AGC	automatic generation control
HP	high pressure cylinder
IP	intermediate pressure cylinder
LP	low pressure cylinder
GEN	electric generator
HHTR	high-pressure heaters
FWP	feed water pump
LHTR	low-pressure heaters
RGA	relative gain array
TMCR	turbine maximum continue rating
MIMO	multi-input-multi-output
PID	proportion-integration-differentiation controller
DHN	district heating networks
DCS	distributed control system

I. INTRODUCTION

In recent years, renewable energy power such as wind power and photovoltaics (PV) has developed rapidly. Since the power generates by wind power and PV is stochastic, controllable energy power is required to compensate for the disturbance of the power grid caused by renewable energy power fluctuations. Among them, energy storage technologies are a hot research topic, including batteries, super capacitors, hydropower, compressed air and other energy storage technologies. However, the cost of compensating for wind power and PV disturbances by adding energy storage devices is high, and the devices are subject to many limitations such as life span, efficiency, and construction site selection [1]. Therefore, the most economical way to compensate for disturbances in the short term is to increase the power generation flexibility of the existing thermal power plant [2]–[6]. In particular, in China, thermal power units are the main power generating units. And as of the end of 2020, coal-fired power unit installed capacity accounted for 56.6% of the total installed capacity [7]. Therefore, improving the flexibility of thermal power units can ease the pressure on the power grid caused by integration of wind power and PV in a short time and with less cost. Since the task of coordinated control system (CCS) of thermal power unit is to follow the automatic generation control (AGC) power generation load command of the grid accurately and quickly, to increase the flexibility of thermal power units is to improve the performance of CCS.

Coal-fired thermal power plants can be divided into two categories: supercritical once-through boiler units and subcritical drum boiler units. Due to high thermal efficiency, most of China's newly built units are the supercritical once-through boiler units. The structure diagram of a typical coal-fired power plant is shown in Fig. 1. The energy storage of a coal-fired power unit mainly exists in coal pulverization system (black part in Fig. 1) and in water-steam system (green part in Fig. 1). Because there is a steam drum in the drum boiler unit as a buffer of energy, the coupling between the feed water system and the fuel combustion system is very weak, so there is no need to consider the influence of the feed water system on CCS of the boiler and the turbine. However, the once-through boiler has no drum buffer which lead difficulties to match the energy released by coal combustion and the energy absorbed by the steam and water. In order to balance the energy of fuel and feed water, the impact of feed water on the unit is added to the once-through boiler CCS, which greatly increases the difficulty of CCS design.

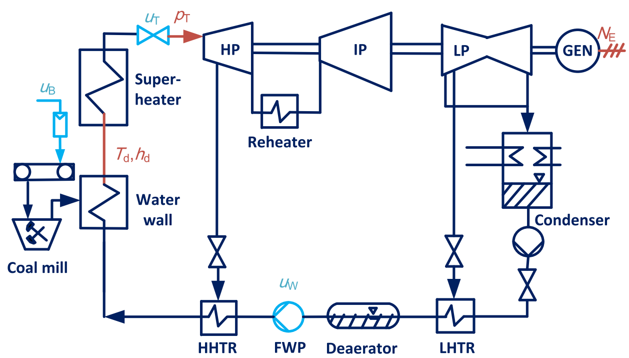


FIGURE 1. Diagram of a coal-fired once-through boiler unit power plant.

The existing CCS research on supercritical once-through boilers is divided into engineering method and theoretical method. In engineering, there are two main control methods: water following CCS and fuel following CCS. For example, the Japanese Mitsubishi and Hitachi control scheme is based on fuel following, whereas the European Alstom scheme is based on water following CCS [8]. Reference [8] compares the characteristics of the two control schemes with actual power plant operating data. Other engineering methods are based on the improvement of the above two schemes. The improvements are mainly two types of method. One is to use different decoupling and compensation methods from the perspective of multivariable design. Reference [9] adopts the switching control scheme in which using fuel following in dynamic process and water following in steady-state.

Reference [10] studies the non-disturbance switching scheme, and applied linear active disturbance rejection controller to optimize CCS. The second method is to find a more suitable controlled variable of the water-steam system, such as temperature, enthalpy, or superheat degree at the intermediate point. Generally, the improved engineering methods has insufficient basis and the parameter selection depends on experience of engineers.

Theoretical research mainly focuses on modeling, monitoring and control. Modeling is the prerequisite for control. Some models are accurate but too complex for control design [11]–[14]. Some models have low precision while can reflect the main dynamic characteristics of the system. They can be used for control method design directly [15], [16] or be used after partial differential equation simplification [17]–[19]. Process monitoring can provide safety assurance and measurement signals for control. Since water-fuel ratio is an important process variable in CCS of once-through boiler, [20] gives two kinds of soft measurement methods to monitor the water-fuel ratio. Reference [21] proposes a dynamic distributed monitoring strategy to separate the dynamic variations from the steady states under closed-loop control. Control is designed on the basis of model. Nonlinear optimal control [22], [23], model predictive control [24], [25], and neural network inverse control [26] are proposed for ultra-supercritical boiler-turbine unit. However, these control methods are too complicated to implement or the reliability is not up to the application in power plants currently. In order to implementation in distributed control system (DCS) of power plants, some methods have been explored and improved on the basis of the engineering scheme. Reference [27] uses water following CCS as the basic scheme, and adds heat storage deviation correction to the feed water flow command. Simulation results show that the advanced control strategy can reduce the power load deviation. Reference [28] discusses using the first-order inertia and second-order inertia links which are commonly used in engineering as feed water compensation, and the simulation results show that the first-order inertia has a better effect.

In this paper, first of all, we establish a dynamic model of the CHP unit with a supercritical once-through boiler. Basing on the model, we analyze the main engineering CCS schemes and found the essential reason for the fluctuation of throttle pressure before turbine. Furthermore, basing on wavelet analysis, a dynamic compensation scheme is designed on the original engineering scheme. Finally, simulation experiments are carried out. The main contribution of the work is as follows.

- Through simulation, relative gain array (RGA) method, and wavelet method, it is analyzed that the difficulty in control of pressure and temperature for the once-through boiler is the coupling between fuel flow and feed water flow. The simulation analyzes the open-loop characteristics of fuel and feed water to pressure and temperature; the RGA number analyzes the coupling characteristics between input-output pairings; and wavelet method analyzes the closed-loop characteristics of the influence of fuel and feed water on pressure. Generally, there are only simulation and open-loop analysis [14], [27], [28], and few closed-loop analysis. The closed-loop analysis of CCS using wavelet method avoids complicated formula derivation, and can intuitively analyze the response characteristics of pressure to fuel and water from the energy point of view.
- A method is proposed to obtain the parameters of the dynamic compensation link through the wavelet coefficients of the closed-loop response. The dynamic parameters in the literature are either obtained through tuning and trial [9], [14]; or they are only derived from the open-loop characteristics without considering the influence of the closed-loop on the parameters [28]. The simulation results show that comparing with the commonly used static compensation in engineering, the dynamic compensation can effectively reduce the throttle pressure and intermediate point temperature fluctuations of CCS when power load command changes.

II. SIMPLIFIED DYNAMIC MODEL OF A CHP PLANT

A reasonable complexity model that can reflect the dynamic characteristics of the plant is a prerequisite for the design of the control method. By comparing the difference between the calculated value of the heat storage coefficient of the once-through boiler and the experimental value, [15] reveals the coupling mechanism between the intermediate point temperature of the once-through boiler and the throttle steam pressure before turbine, and then the core model of the once-through boiler steam-water system is obtained. Since, the structure of the thermal system of a typical extraction CHP unit is similar to that of a pure condensing unit, except for the heating part, the supercritical once-through CHP unit model is obtained by combining the supercritical once-through condensing unit model [15] and the drum boiler CHP unit model [6].The simplified dynamic unit model is described as (1)-(12). The modeled unit has a supercritical parameter once-through circulation boiler HG-1110/25.4-HM, and a supercritical steam parameter heating condensing steam turbine C350/277-24.2/0.4/566/566.

$$r_{\mathrm{M1}} = u_{\mathrm{B}}(t-\tau_{\mathrm{f}}) \tag{1}$$
$$T_{\mathrm{f1}} dr_{\mathrm{M2}}/dt = -r_{\mathrm{M2}} + r_{\mathrm{M1}} \tag{2}$$
$$T_{\mathrm{f2}} dr_{\mathrm{B}}/dt = -r_{\mathrm{B}} + r_{\mathrm{M2}} \tag{3}$$
$$C_{\mathrm{m}} dT_{\mathrm{d1}}/dt = -K_8 q_{\mathrm{W}} h_{\mathrm{d1}} + K_1 r_{\mathrm{B}} \tag{4}$$
$$h_{\mathrm{d1}} = T_{\mathrm{d1}} - 5.6(p_{\mathrm{d}} - 27) - 174 \tag{5}$$
$$T_{\mathrm{d}} = T_{\mathrm{d1}}(t-\tau_{\mathrm{d}}) \tag{6}$$
$$h_{\mathrm{d}} = 8(T_{\mathrm{d1}} - 425) - 45(p_{\mathrm{d}} - 27) + 2735 \tag{7}$$
$$T_{\mathrm{w}} dq_{\mathrm{w}}/dt = -q_{\mathrm{w}} + u_{\mathrm{W}} \tag{8}$$
$$C_{\mathrm{v}} dp_{\mathrm{d}}/dt = -K_3 p_{\mathrm{t}} u_{\mathrm{T}} + K_8 q_{\mathrm{W}} h_{\mathrm{d1}} \tag{9}$$
$$p_{\mathrm{t}} = p_{\mathrm{d}} - K_2 q_{\mathrm{w}}^{1.5} \tag{10}$$
$$T_{\mathrm{t}} dN_{\mathrm{E}}/dt = -N_{\mathrm{E}} + K_6 u_{\mathrm{L}} p_{\mathrm{e}} + K_3(1-K_5) p_{\mathrm{t}} u_{\mathrm{T}} \tag{11}$$
$$T_{\mathrm{e}} dp_{\mathrm{e}}/dt = K_3 K_5 p_{\mathrm{t}} u_{\mathrm{T}} - K_6 u_{\mathrm{L}} p_{\mathrm{e}} - K_7 u_{\mathrm{E}} p_{\mathrm{e}} \tag{12}$$

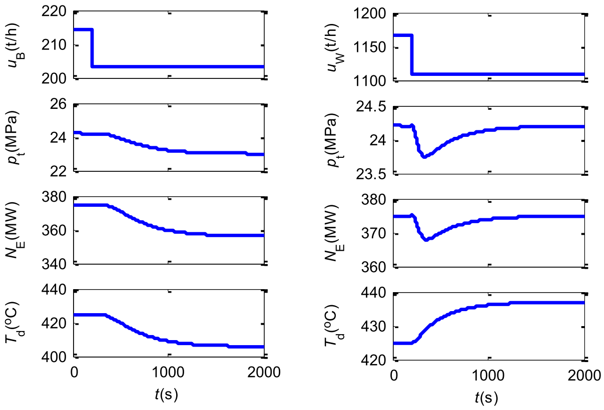


FIGURE 2. Step responding curves of fuel flow and feed water flow.

The model contains five control input variables, which are the fuel flow u_B (t/h), the opening of regulating valve of the high-pressure cylinder (HP) of turbine u_T (%), the feed water flow u_W (t/h), the opening of regulating butterfly valve of heating extraction u_E(%), and the opening of low-pressure cylinder inlet valve u_L(%). The model has five output variables, which are throttle pressure before turbine p_t (MPa), the power load N_E (MW), the intermediate point temperature T_d(°C), the specific enthalpy of intermediate point h_d (kJ/kg), and the heat extraction pressure p_e (MPa). The intermediate variables are the boiler fuel flow rate r_B (kg/s), the feed water flow of phase change section q_W (kg/s), and the pressure of steam water separator p_b (MPa). The dynamic parameters are as follow, the delay time of the pulverizing process and the slightly superheated section τ_f, τ_d (s), the inertial time constant T_{f1}, T_{f2} (s), and the heat storage coefficient of boiler metal and steam-water system C_m, C_v (MJ/MPa). The other intermediate variables and dynamic and static parameters are described in [15].

Since this paper mainly studies the impact of feed water on coordinated control system (CCS) of once-through boiler unit, only the characteristics of the CHP unit under pure condensing conditions are considered, that is, setting $u_L = 100$, $u_E = 0$ in the model. The model is built in MATLAB/Simulink. The initial stable working condition is turbine maximum continue rate (TMCR) (power load N_E is 374.9MW, throttle pressure p_t is 24.2MPa, and the intermediate point temperature T_d is 425°C). At 200s, −5% step disturbance experiment of fuel flow u_B and feed water flow u_W is done separately, and the main parameter response are shown in Fig.1. In Fig. 1 a), when the fuel flow decreases, the unit power load, throttle pressure, and intermediate point temperature all slowly decrease to the new steady-state value. In Fig. 1 b), when the feed water flow decreases, the pressure and the power load both decrease first and then slowly increase and restore the steady state value before the disturbance; the temperature at the intermediate point slowly increases to the new steady state value. The water-fuel ratio control takes advantage of the opposite characteristics of the fuel flow and the feed water flow to the temperature of the intermediate point. When the ratio is appropriate, the temperature of the intermediate point can be kept constant. In other words, the temperature represents the heat balance between the input fuel and water. When the temperature remains unchanged, the coordinated control system of the once-through boiler unit can be equivalent to the coordinated control system of the drum boiler unit for design and tuning. However, it is a difficult problem to keep the fuel flow and the feed water flow in a proper ratio during the dynamic process. Although many scholars and engineers have made various studies and attempts, different control methods have their own advantages and disadvantages.

III. RGA ANALYSIS ON DIFFERENT SCHEMES OF COORDINATED CONTROL SYSTEM

A. RGA ANALYSIS

The model of the CHP unit is a multi-input-multi-output (MIMO) plant. Relative gain array (RGA) method is an effective characteristic analysis method in MIMO systems and is widely used in process control [6]. For subsequent RGA analysis, a linear model is needed. The transfer function matrix models are derived by small deviation linearization of the model (1)-(12) at TMCR working condition. Since pure condensing conditions are considered, u_L, u_E are constant and p_e does not affect CCS. Thus, the three-input three-output linear model is shown in (13).

$$\begin{bmatrix} p_t(s) \\ T_d(s) \\ N_E(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) & G_{13}(s) \\ G_{21}(s) & G_{22}(s) & G_{23}(s) \\ G_{31}(s) & G_{32}(s) & G_{33}(s) \end{bmatrix} \cdot \begin{bmatrix} u_B(s) \\ u_W(s) \\ u_T(s) \end{bmatrix} \quad (13)$$

RGA of non-singular square matrix G is defined as,

$$\mathrm{RGA}(\boldsymbol{G}) = \Lambda(\boldsymbol{G}) = \boldsymbol{G} \odot (\boldsymbol{G}^{-1})^{\mathrm{T}} \quad (14)$$

where, $\odot$ is a binary operation that takes two matrices of the same dimensions, and produces another matrix where each element i, j is the product of elements i, j of the original two matrices (Schur production).

For a diagonal pairing, its RGA number is,

$$\text{RGA number} = \|\Lambda(\boldsymbol{G}) - \boldsymbol{I}\|_{\text{sum}} \quad (15)$$

where, summation norm $\|\boldsymbol{A}\|_{\text{sum}} = \Sigma_{ij} \mid a_{ij} \mid$. For non-diagonal pairing, RGA number can be derived by subtracting 1 from the paired position.

Effective pairing of input-output is gained by several simple RGA pairing rules. We tend to choose pairing which has a small RGA number, especially in the working bandwidth. For the three-input three-output once-through boiler plant, there are a total of 6 input-output pairing schemes, as shown in the Table 1.

The RGA number of 6 schemes under different frequency is calculated, and the results are shown in Fig. 3. Scheme 5 and 6 are first excluded because RGA numbers are large in the working frequency band (between 0.001 and 0.01 rad/s). The average RGA numbers of the other 4 schemes

TABLE 1. Pairing schemes of multivariable control.

1	2	3	4	5	6
u_B - N_E	u_B - T_d	u_B - T_d	u_B - p_t	u_B - p_t	u_B - N_E
u_W - T_d	u_W- N_E	u_W - p_t	u_W - T_d	u_W- N_E	u_W - p_t
u_T - p_t	u_T - p_t	u_T - N_E	u_T - N_E	u_T - T_d	u_T - T_d

are smaller. Therefore, pairing 1 with a smaller RGA number is selected, and pairs 2, 3, and 4 are used as alternatives.

B. FUEL FOLLOWING CCS CONTROL SCHEME

Let's analyze these pairing schemes from the perspective of engineering practicality. Under pairing 1, the power load controlled by fuel flow responds too slow to meet the AGC requirement, so pairing 1 is only used when the important auxiliary machine fails, and it is not used under normal circumstances. Pairing 2 is generally not used in practice, because the reliability of feed water flow system cannot meet the high reliability requirements of the power load. Pairing 3 and 4 correspond to two types of commonly used engineering schemes, and an introduction is given below.

In CCS of the supercritical once-through boiler unit, the feed water and fuel regulation systems coordinate their actions and cooperation correctly, so that the boiler load meets the requirements and the superheated steam temperature is basically stable. Since the changes in fuel flow and feed water follow have obvious effects on output power, there are two different principle schemes for the power load regulation of once-through boiler unit. One scheme (pairing 3 in Table 1 and Fig.3) is to use fuel flow as the active manipulated variable of the CCS to regulate the power load or the throttle pressure, and use feed water flow as the driven manipulated variable to adjust the temperature or enthalpy of the slightly superheated steam at the intermediate point to ensure the water-to- fuel ratio, which is usually called water following CCS scheme. The other scheme (pairing 4 in Table 1 and Fig.3) is to take the feed water flow as the active manipulated variable to adjust the power load or throttle pressure and use the fuel flow as the driven manipulated variable to adjust the temperature or enthalpy of the intermediate point to ensure the water-to-fuel ratio, which is usually called fuel following CCS scheme. The characteristics of these two control schemes are explained below.

Simplified control structure of fuel following CCS is shown in Fig. 4. The power load is controlled by the opening of regulating valve of HP, the throttle pressure is controlled by feed water flow, and the temperature or enthalpy of intermediate point is controlled by fuel flow. The output of the feed water controller PID2 is added to the main control of the furnace through the compensation link. The characteristic of this control scheme is that the unit responds quickly to external load changes, but the throttle pressure and the temperature at the intermediate point fluctuate greatly. Generally speaking, throttle pressure of the fuel following CCS responds better

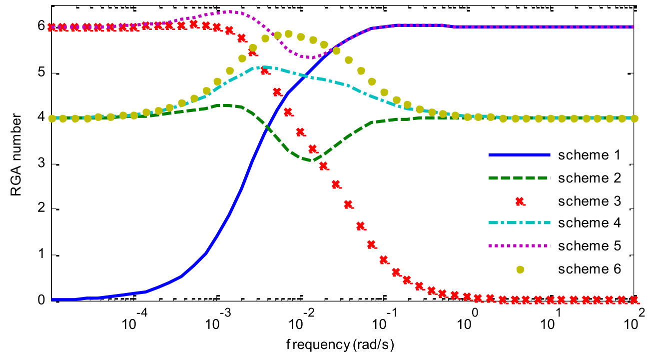


FIGURE 3. RGA number of six input-output pairing schemes.

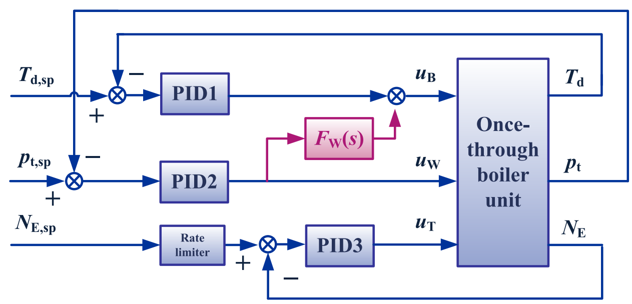


FIGURE 4. Fuel following CCS for once-through unit.

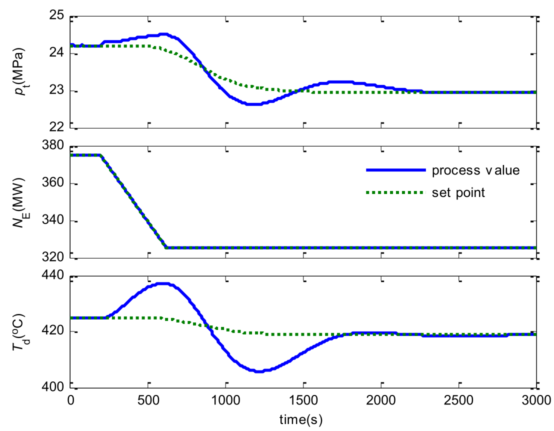


FIGURE 5. Disturbance experiment of AGC command with fuel following CCS.

than that of water following CCS. The following simulation illustrates the above-mentioned characteristics of the fuel following CCS control scheme.

The transfer functions of controllers in Fig. 4 are shown in (16)-(20). Under the initial stable working condition TMCR, $N_{E,sp}$, also known as automatic generation control (AGC) command, steps under the rate of 7MW/min at 200s. Then, the responding curves of the unit are derived in Fig. 5. The power load responds fast and accurate; the throttle pressure fluctuates during the dynamic process; the intermediate point enthalpy fluctuates sharply. More precisely, the maximum deviation between the pressure and the set point value is 0.48Mpa, and the maximum deviation between the temperature and the set point value is 13.5°C.

$$C_{PID1}(s) = 80 + \frac{0.5}{s} + \frac{5000}{1+100s} \tag{16}$$
$$C_{PID2}(s) = 0.2 + \frac{0.0018}{s} + \frac{100}{1+100s} \tag{17}$$
$$C_{PID3}(s) = 0.6 + \frac{0.06}{s} \tag{18}$$
$$F_w(s) = 1/5.448 \tag{19}$$

C. WATER FOLLOWING CCS CONTROL SCHEME

Simplified schematic of water following CCS is shown in Fig. 6. The power load is controlled by the opening of regulating valve of HP, the throttle pressure is controlled by fuel flow, and the temperature or enthalpy of intermediate point is controlled by feed water flow. The output of the fuel controller PID1 is added to the water controller through the compensation link. The characteristic of this control scheme is that the unit responds quickly to external load changes, but the throttle pressure and the temperature at the intermediate point fluctuate greatly. Generally speaking, temperature of the water following CCS responds better than that of fuel following CCS. The following simulation illustrates the above-mentioned characteristics of the water following CCS control scheme.

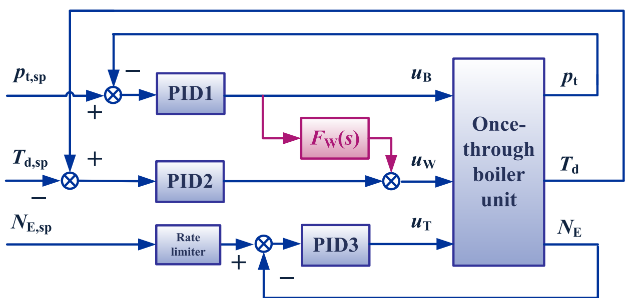


FIGURE 6. Water following CCS for once-through unit.

The transfer functions of controllers in Fig.6 are shown in (20)-(23). Under the initial stable working condition TMCR, AGC command steps under the rate of 7MW/min at 200s, the responding curves of the unit are shown in Fig. 7. The power load responds fast and accurate; the throttle pressure deviation during the dynamic process is large; the intermediate point enthalpy fluctuates sharply. More precisely, the maximum deviation between the pressure and the set point value is 0.61Mpa, and the maximum deviation between the temperature and the set point value is 10.7°C.

$$C_{PID1}(s) = 22 + \frac{0.09}{s} + \frac{2000}{1+100s} \tag{20}$$
$$C_{PID2}(s) = 2.4 + \frac{0.016}{s} + \frac{800}{1+100s} \tag{21}$$
$$C_{PID3}(s) = 0.6 + \frac{0.06}{s} \tag{22}$$
$$F_w(s) = 5.448 \tag{23}$$

Since the above two common engineering schemes have their own advantages and disadvantages in control (better pressure and worse temperature performance in fuel following scheme, and better temperature and worse pressure performance in water following scheme), we return to analyze the RGA number (Fig. 3) and find that the average RGA number of the two schemes in the working frequency band is similar. Since the RGA number in pairing 4 basically does not change with frequency, we choose water following CCS as the basic control scheme. Next, to improve pressure performance (Fig. 7), we will use wavelet analysis to design the compensation link in water following CCS scheme.

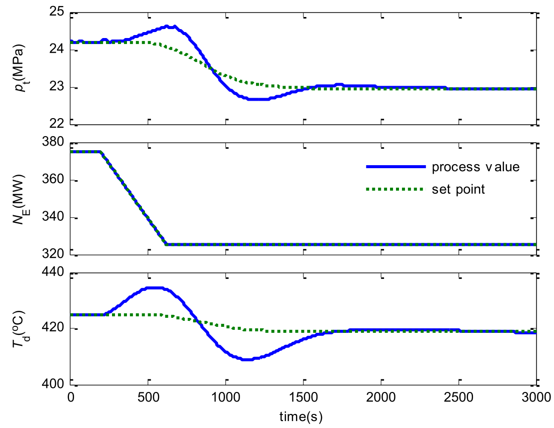


FIGURE 7. Disturbance experiment of AGC command with water following CCS.

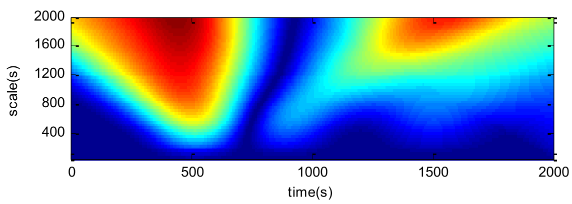
IV. COMPENSATION DESIGN OF WATER FOLLOWING CCS

A. WAVELET ANALYSIS ON CCS WITHOUT COMPENSATION

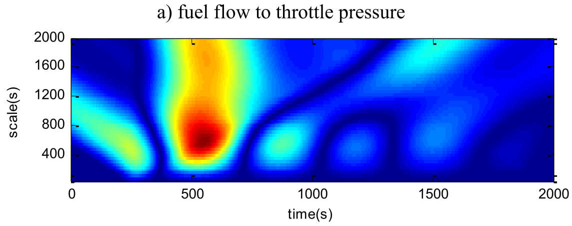
Since the design of closed-loop control system has an impact on the coupling characteristics of the CHP plant, it is not enough to analyze the coupling characteristics of the open-loop object. The closed-loop analysis of CCS using wavelet method avoids complicated formula derivation, and can intuitively analyze the response characteristics of pressure to fuel and water from the energy point of view. Wavelet transform can perform localized analysis of signal time domain and frequency domain. It gradually refines the signal at multiple scales through expansion and translation operations. The magnitude of the wavelet coefficient at a certain point in the coefficient graph reflects the similarity between the signal and the wavelet at a certain scale and at a certain time. The wavelet coefficient can reflect the fluctuation degree of the signal, that is, the magnitude of the signal energy [29]. Observing the change trend of wavelet coefficients, we can get the characteristics of the signal at different scales.

The simulation platform is MATLAB/Simulink, and the simulation step length is 1s. The control scheme is shown in Fig.6 without compensation link. Under the TMCR working condition, the step disturbance experiments of the fuel flow, the feed water flow, and the opening of regulation valve of high-pressure cylinder were carried out separately from 200s, and the three sets of pressure response curves were obtained. Comparing commonly used wavelets, it is found that the time-domain shape of *gaus1* wavelet is closest to several sets of closed-loop response curves, so the continuous wavelet transform coefficient graph of *gaus1* can best reflect the fluctuation characteristics of the signal.

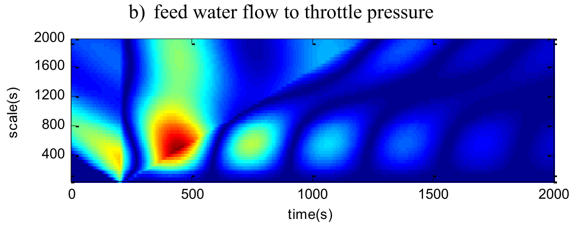
The *gaus1* wavelet is used to decompose the three sets of pressure signals in multi-scale of time, and the normalized wavelet coefficients are shown in Fig. 8 (the red represents the large wavelet coefficient, and the blue represents the small coefficient). Comparing Fig. 8 a) and b), c), from the time axis, the response of throttle pressure to fuel flow lags behind that of the feed water and the opening of regulating valve of HP. From the scale axis, the energy response of the fuel flow is distributed on a higher scale. The response of the valve opening and feed water is concentrated on the low-level. Because the scale is inversely proportional to the frequency, that is to say, the throttle pressure fluctuations caused by the fuel flow disturbance are mainly low-frequency fluctuations, while the steam turbine side and the feed water side are higher frequency fluctuations, which is consistent with common sense. From Fig. 9 a) and b), c), it is clear that the energy distribution of the three has a large gap, which is the main reason that the throttle pressure is difficult to control in CCS.



a) fuel flow to throttle pressure



b) feed water flow to throttle pressure



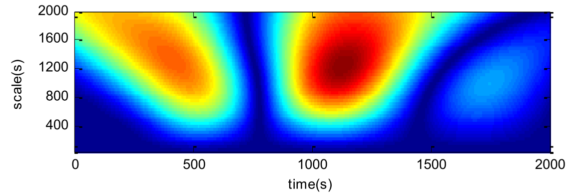
c) opening of regulating valve of the high-pressure cylinder to throttle pressure

FIGURE 8. Energy distribution of throttle pressure to different inputs in closed loops.

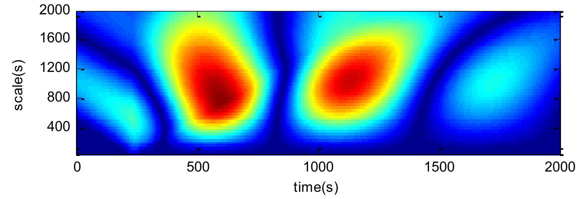
B. WAVELET ANALYSIS ON CCS WITH STATIC COMPENSATION

The control scheme is shown in Fig.5 with static compensation link, which is the most commonly used compensation method in engineering. The static compensation coefficient is generally obtained through power load conversion in engineering. Since we have established the model of the plant, the static compensation coefficient can be calculated from (13).

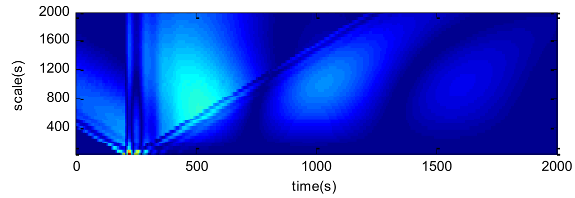
The simulation platform is MATLAB/Simulink, and the simulation step length is 1s. Under the TMCR working condition, the step disturbance experiments of the fuel flow, the feed water flow, and the opening of regulation valve of high-pressure cylinder were carried out separately from 200s, and the three sets of pressure response curves were obtained. The gaus1 wavelet is used to decompose the three sets of pressure signals in multi-scale of time, and the normalized wavelet coefficients are shown in Fig. 9 (the red represents the large wavelet coefficient, and the blue represents the small coefficient).



a) fuel flow to throttle pressure



b) feed water flow to throttle pressure



c) opening of regulating valve of the high-pressure cylinder to throttle pressure

FIGURE 9. Energy distribution of throttle pressure to different inputs in closed loops.

Compared with Fig. 8 a), the scale of the disturbance caused by the fuel flow in Fig. 9 a) is significantly reduced, which shows that the influence of the high-frequency disturbance of the fuel flow on throttle pressure is reduced. In the actual operation of the unit, the fuel flow often changes frequently, so the static compensation is beneficial to stabilize the throttle pressure. Compared with Fig. 8 a) and b), the difference between the influence of fuel flow and feed water flow on pressure in Fig. 9 a) and b) is reduced, so that the feed water flow can compensate for the pressure disturbance caused by fuel changes in time, but the two are still not aligned in time domain. Judging from the darkest red parts in Fig. 9 a) and b), the maximum disturbance caused by fuel flow lags behind the maximum disturbance caused by water flow. Therefore, to improve the throttle pressure performance further, you need to align the responses of water and fuel

TABLE 2. Wavelet coefficients and compensation segment parameters.

Number	Coefficient *a*	Coefficient *b*	Time *a*	Time *b*	Gain	Time constant
1	23.0821	4.2354	1147	607	5.4498	135
2	23.0819	4.2354	1146	608	5.4498	135
3	23.0818	4.2351	1148	606	5.4502	136
4	23.0813	4.2351	1145	609	5.4500	134
5	23.0812	4.2345	1149	605	5.4508	136
6	23.0803	4.2344	1144	610	5.4506	134
7	23.0802	4.2336	1150	604	5.4517	137
8	23.0789	4.2335	1143	611	5.4515	133
9	23.0788	4.2324	1151	603	5.4529	137
10	23.0771	4.2322	1142	612	5.4528	133

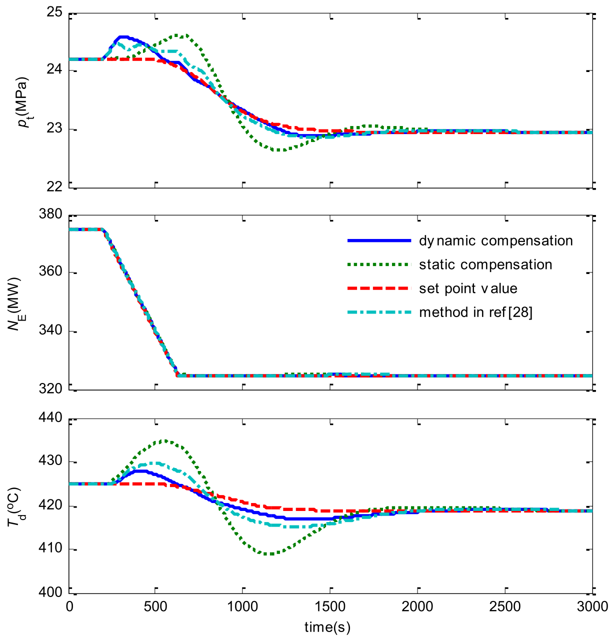


FIGURE 10. Comparisons of step responses to AGC command.

in time domain. That is to say, you need to design dynamic compensation.

C. DESIGN OF DYNAMIC COMPENSATION

The compensation link is designed to compensate for reducing fluctuation of throttle pressure before turbine (in Fig. 6). The energy of fuel and water can be balanced by setting the gain, and the difference in time can be aligned by inertia. Therefore, the first-order inertial link commonly used in engineering is selected as the compensation structure.

We select the two groups of wavelet coefficients with the most violent fluctuations (red area) in Fig. 9 a) and b) and their corresponding time components (Table 2). The gain of the compensation link is wavelet coefficient *a*/wavelet coefficient *b*, the inertial time constant is (time *a*-time *b*)/3. Take the average value to get the compensation segment

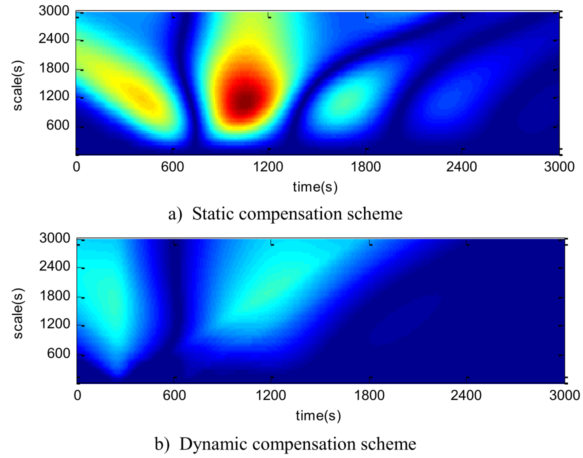


FIGURE 11. Energy distribution of throttle pressure in different control schemes.

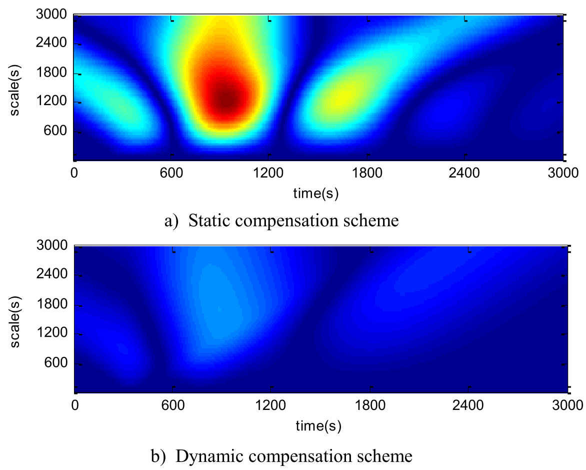


FIGURE 12. Energy distribution of intermediate point temperature in different control schemes.

as 5.45/(1+135s). If this compensation link is adopted, the fuel flow will be changed at the beginning of the load change, and the feed water flow will be changed after the fuel combustion energy is absorbed by the water-steam system to balance the energy of coal and water.

V. SIMULATION AND ANALYSIS

The simulation platform is MATLAB/Simulink, and the simulation step length is 1s. The schemes for comparison include water following CCS with dynamic compensation proposed in this paper, water following CCS with static compensation commonly used in practice, water following CCS with dynamic compensation proposed in [28], and fuel following CCS with static compensation commonly used in practice. The initial stable working condition is TMCR (power load N_E is 374.9MW, throttle pressure p_t is 24.2MPa, and the intermediate point temperature T_d is 425°C). The power load command steps from 374.9MW to 324.9MW at 200s under the rate of 7MW/min. Response curves in Fig. 10 (for a clearer display, simulation of fuel following CCS is

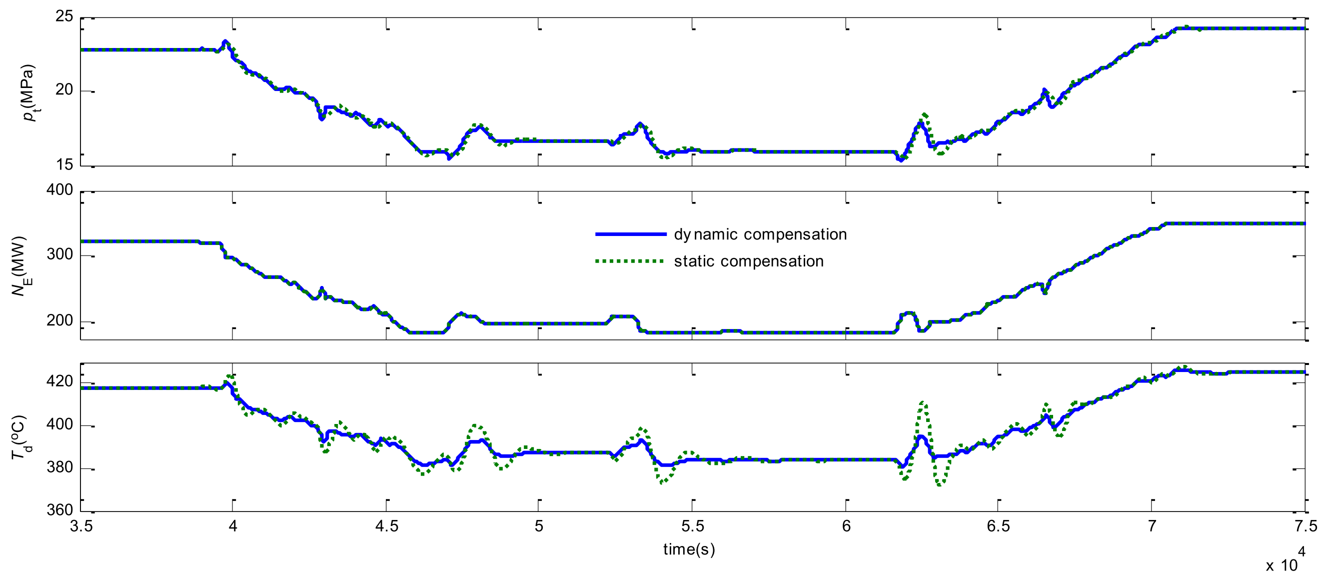


FIGURE 13. Comparisons of responses to actual AGC command disturbance.

shown in Fig.5) show that the power load of the all schemes can quickly and accurately follow the load command, and the pressure and temperature fluctuation in the dynamic compensation scheme is obviously small.

Table 3 illustrates the response characteristics of the four schemes. The maximum deviation represents the maximum absolute value of the deviation between the process variable and the set point value. And the peak time is another commonly used index to evaluate the dynamic response characteristics of the control system. It is the time from the start of the set point value disturbance to the peak value of the variable. Table 3 shows that dynamic compensation schemes (row 1 and row 3) have smaller maximum deviations and shorter peak time than static compensation schemes (row 2 and row 4). Comparing the two static schemes, the dynamic response of pressure in water following CCS (row 2) is worse than that of fuel following CCS, and the dynamic response of temperature in water following CCS (row 2) is better than fuel following CCS. Comparing the two dynamic schemes, the dynamic response of pressure in [28] is faster than our scheme (row 1), whereas it has small fluctuations which is do not want to appear in power plant pressure object. And the temperature dynamic response of our scheme (row 1) is better than that of [28].

Let's analyze the response curves from the view of energy. The schemes for comparison include water following CCS with dynamic compensation proposed in this paper and water following CCS with static compensation commonly used in practice. In the static compensation scheme, the shape of the fluctuations of the throttle pressure and the temperature at the intermediate point are similar, but the pressure change lags behind the temperature change. If the pressure is not adjusted in time, the fuel flow will fluctuate, which will drive the fluctuation of the feed water flow and make the steam temperature difficult to stabilize. It can be seen that the pressure and temperature affect each other, causing the curve to fluctuate greatly. Moreover, when tuning the controller parameters, a slight deviation will cause the curves to fluctuate and they will not return to the set point value for a long time. In the dynamic compensation scheme, the throttle pressure and the intermediate point temperature fluctuate in a similar shape, while the pressure response is slightly faster than the temperature. Once the pressure is stabilized, the fuel flow will not fluctuate, and the faster response feed water flow is used to adjust the intermediate temperature. Thus, it is easy to make the intermediate temperature reach a steady state.

TABLE 3. Response characteristics of different schemes.

Control scheme	Maximum $\lvert p_t - p_{t,sp}\rvert$	Peak time of p_t	Maximum $\lvert T_d - T_{d,sp}\rvert$	Peak time of T_d
Dynamic compensation	0.39	121	2.9	215
Static compensation	0.61	487	10.7	368
Method in ref[28]	0.26	85	4.7	303
Fuel following CCS	0.48	433	13.5	430

Wavelet analysis was performed on the two curves of throttle pressure and intermediate point temperature in Fig. 10. The results are shown in Fig. 11 and Fig. 12 (the sub-graphs in the figures use the same color scale). The dynamic compensation scheme is bluer and more evenly distributed in color, indicating that the pressure and temperature at the intermediate point have small fluctuations and the energy distribution is more uniform. This is conducive to the stable operation of coordinated subsystems such as fuel, feed water, and air supply.

Take a period of actual AGC command as the input of the control system and observe the change of the output of the system (Fig. 13). This command includes various set point changes such as a large range of load increase, a large range of load reduction, and a small range of load fluctuations. Simulation show that the power load of the two schemes can quickly and accurately follow the AGC command, the pressure responses faster and the temperature fluctuation is obviously smaller in the dynamic compensation scheme.

VI. CONCLUSION

A supercritical once-through boiler CHP unit model is established, and comparison of the two common engineering CCS schemes with static compensation is done by simulation. The results show that, the water following CCS scheme has better intermediate point temperature performance and worse throttle pressure performance than the fuel following CCS scheme. To improve the poor pressure performance of the water following CCS scheme, the closed-loop characteristics of pressure response to fuel and feed water flow are analyzed and compared through wavelet coefficients, and then a method for determining the inertia time constant in the dynamic compensation link by comparing the wavelet coefficients is proposed. Simulation results show that when the AGC command changes, comparing with the static compensation, the dynamic compensation scheme proposed in this paper can greatly reduce the intermediate point temperature fluctuation and the throttle pressure fluctuation.

The imbalance of energy released by fuel combustion and energy absorbed by water-steam system is the essential cause of large fluctuations in intermediate point temperature and throttle pressure before turbine of CCS for the supercritical once-through boiler unit. We analyze it from multiple angles. The simulation analyzes the open-loop characteristics and finds the response caused by fuel flow is slow and the response to feed water flow is fast. The RGA number analyzes the coupling characteristics between input-output pairings and finds that coupling exists in pairing schemes 3 and 4. And wavelet method analyzes the closed-loop characteristics and finds that the responses of fuel flow and feed water flow are very different on the time scale in the water following CCS scheme with only static compensation link and the imbalance in the speed of energy changes is the essential cause of large fluctuations in temperature and pressure. Moreover, wavelet analysis shows that the dynamic compensation CCS can improve this energy imbalance.

In this paper, we study the CCS of the CHP plant under pure condensing condition, in which the controlled object can be simplified into a three-input three-output object. Since the CHP plant can use thermal inertia of the district heating network to increase the flexibility of power generation through EV and LV under heating condition. We will study CCS under heating condition in future work. Then, the entire controlled object becomes a more complicated five-input and five-output object. The closed-loop characteristic analysis method proposed in this work may be extended to the heating conditions.

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TUOYU DENG was born in Baoding, Hebei, China, in 1987. She received the B.S. degree in measurement and control technology and instruments from North China Electric Power University, Baoding, China, in 2009, and the M.S. and Ph.D. degrees in control theory and control engineering from North China Electric Power University, Beijing, in 2012 and 2016, respectively.

Since 2016, she has been an Instructor with the School of Control and Computer Engineering, North China Electric Power University. Her research interests include modeling and control of thermal power plant, and artificial intelligence.

LIANG TIAN was born in Inner Mongolia, China, in 1976. He received the B.E., M.S., and Ph.D. degrees in engineering from North China Electric Power University, in 1997, 2000, and 2005, respectively.

He is currently an Associate Professor and a Master Tutor of North China Electric Power University, and a Permanent Researcher with the State Key Laboratory of New Energy Power System. His research interests include modeling, parameter soft measurement and optimization control of thermal power plants, flexibility of power plants, and big data application.

Dr. Tian won the Second Prize of the China Power Technology Award.

CHENGXI ZHOU was born in 1962. He is currently a Senior Engineer. He is also the Deputy Director of the Department of Construction, State Grid Liaoning Electric Power Company Ltd., Shenyang, China. His research interests include power systems and electric-thermal energy systems.

XINPING LIU was born in Tangshan, Hebei, China, in 1975. She received the B.E. degree in centralized control operation from the Department of Power Engineering, North China Electric Power University, in 1997, and the M.S. and Ph.D. degrees in control theory and control engineering and thermal energy engineering from North China Electric Power University, in 2000 and 2010, respectively.

She is currently an Associate Professor and a Master Tutor of North China Electric Power University. Her research interests include intelligent optimization control of large units, thermal power generation process modeling and status parameter detection, and deep peak shaving technology for thermal power units under the conditions of large-scale grid connection of new energy.

WENLEI DOU was born in 1979. He received the B.E. degree from Shenyang Agricultural University. He is currently pursuing the M.S. degree. He is also a Senior Engineer with State Grid Liaoning Electric Power Company Ltd., Shenyang, China. His research interests include power grid planning and electric-thermal energy systems.