Model of thermal power plant considering water spray desuperheater for power system analysis

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Abstract. It is of great significance to build a model of the water spray temperature reduction system that is more suitable for electrical simulation, and apply it to the existing thermal power plant model for the simulation analysis of today's complex thermal power plants. Based on reasonable thermodynamic assumptions, the law of conservation of energy and the law of conservation of mass, a transfer function model of a water-jet cooling system suitable for the simulation of a thermal power plant is established by using mechanism modeling. The relationship between these variables and the effect of each variable on the output variables verified the correctness of the model. A steam turbine system considering the influence of the boiler was further established, and a simulation analysis of the operating characteristics was performed, which verified that the influence of the boiler on the dynamic response of the unit is necessary in the long-term stability analysis. Finally, combined with the model established in this paper, a dynamic model of thermal power unit with water spray temperature reduction device was established. The model is simulated with the step disturbance of velocity, the disturbance of cooling water flow and the disturbance of opening door. Based on the simulation results, the action response characteristics in the process are analyzed. It is verified that the model can accurately describe the main steam parameters and power regulation when applied to large-scale power grid transient simulation.

1. Introduction
The boiler spray desuperheating device is indispensable in large-scale thermal power units. Its function is to regulate, cool down the superheated and large flow steam flowing through the boiler [1], which is an important guarantee for the safe operation of the boiler and the steam turbine, so that the steam temperature entering the steam turbine is within the normal operation range of the unit. In case of sudden change of unit operation conditions, especially after fast load rejection (FCB) of steam turbine unit, the temperature control of steam generated by boiler has an important connection with coordinated operation of steam turbine [2]. The reliability of the spray desuperheating system not only directly affects the main equipment of the boiler and steam turbine in the thermal power unit, but also the auxiliary equipment, such as the regenerative heater and the steam pump turbine, etc.; moreover, because the spray desuperheating system affects the temperature and pressure of the main steam, the change of the temperature and pressure of the main steam affects the enthalpy of the steam entering the steam turbine, and the change of the corresponding main steam's power generation capacity results in the change of the power generation capacity The unit output fluctuates greatly, which affects the operation and safety of the large power grid associated with the generator [3]. Therefore, it is
necessary to study more suitable spray desuperheating system model and its operation characteristics in order to study its influence on the operation characteristics of thermal power units [4-6].

At present, the boiler spray desuperheater has been deeply studied from the perspective of thermal power engineering at home and abroad. In Reference [7], a modular Simulink library of components such as valves, turbines, and heaters has been developed. In this way, it is possible to easily assemble and customize models able to simulate different plants and operating scenarios. In Reference [8], a spray desuperheating system model is proposed, and the nonlinear mathematical model of each module describing the air temperature system is obtained by using the method of mechanism modeling. Furthermore, in Reference [9], based on the principle of mass and energy balance, the mathematical model and mechanism control model of spray desuperheater are established from the micro and macro levels respectively. In Reference [10], the boiler system model is established and the boiler start-up process is simulated. The simulation results are consistent with the actual process. In Reference [11], a dynamic mathematical model of a 600MW supercritical once through boiler steam generator, which is suitable for simulating the moving boundary of nonlinear lumped parameters under large disturbance conditions, is established to solve the problem of model switching. In the current large power grid transient simulation analysis [12], there is a lack of boiler spray desuperheater and other models, which is difficult to accurately reflect some dynamic characteristics of thermal power system of thermal power units. According to the simulation requirements of different application scenarios, the relevant literature establishes the corresponding simulation model. What’s more, in Reference [13], the single reheat turbine model considering the influence of boiler is studied. In Reference [14], considering the steam water cycle process of the whole thermal system, a simulation model of unit reheat condensing steam turbine is established, which can take into account the effect of regenerative system and Reheater on the dynamic response of the unit. In Reference [15], a coordinated control model suitable for the whole process simulation of electromechanical transient and medium and long term dynamic of power system is proposed, which can flexibly simulate the common configuration modes in the boiler control of thermal power plants. In Reference [16], the turbine model with bypass system and the prime mover speed control system model with FCB Function are established.

Based on the mechanism modeling method, the mathematical model of spray desuperheater is established firstly. Combined with the dynamic stability simulation requirements of power system, the applicable transfer function is obtained by linearization and Laplace transformation. The model of steam turbine system considering the influence of boiler and spray desuperheater is established and applied to the simulation analysis of dynamic characteristics of thermal power unit. The validity of the model is verified by the simulation and the actual measurement.

2. Mathematical model of thermal system of thermal power plant

2.1. Dynamic model of spray desuperheating system

Spray desuperheater is used to regulate, depressurize and cool down large flow steam. The heat and mass transfer process between desuperheating water and high temperature and high pressure steam can be modeled simply. According to the requirements of power system dynamic simulation modeling, the following assumptions are set: (1) The cross-sectional area of the inlet and outlet of the water spray desuperheater is approximately equal; (2) the superheated steam and desuperheating water are fully and evenly mixed with the same velocity; (3) the mixed steam in the desuperheater only moves in one dimension along the axial direction; (4) the state parameters of the mixture on each cross section of the desuperheater pipe are uniform; (5) The whole system is in adiabatic state; (6) ignoring the axial heat transfer and radial temperature gradient; (7) ignoring the wall heat transfer process.

2.1.1. Superheater model. The superheater is a part of the boiler that further heats the steam from the saturated temperature to the superheated temperature. After the saturated steam is heated to the superheated steam, the power capacity of the steam in the steam turbine is improved, that is,
Meanwhile, enthalpy drop of the steam in the steam turbine is increased, so the cycle efficiency is improved. The whole process follows the conservation of mass and energy.

In Figure 1, $V$ is the volume of steam, $\rho_2$ is the density of steam outlet; $D_1$ and $D_2$ are the mass flow of steam inlet and outlet; $h_1$ and $h_2$ are the specific enthalpy of working medium inlet and outlet; $Q_{in}$ is the heat exchange of working medium and metal pipe wall in the pipe; $\rho_1$, $P_1$ and $P_2$ are the density of working medium inlet, inlet pressure of working medium in pipe and outlet pressure of working medium in pipe; $t_1$, $t_2$, flue gas inlet temperature and outlet temperature outside the pipe; $t_m$ is the average wall temperature; $Q_{ex}$ and $S_{ex}$ are the heat exchange capacity and heat exchange area of flue gas to metal respectively; $m_m$ is the mass of pipe wall.

$$
\begin{align*}
D_1 - D_2 &= V \frac{d\rho_2}{d\tau} \\
Q_{in} + D_1 h_1 - D_2 h_2 &= V \frac{d(\rho_1 h_1)}{d\tau} \\
P_1 - P_2 &= \xi D_2^2 \\
Q_{ex} &= \alpha_ex S_ex \left( \frac{t_1 + t_2}{2} - t_m \right) \\
Q_{in} &= k_n D_g (t_m - t_2) \\
Q_{ex} &= KD_c (c_1 t_1 - c_2 t_2) \\
Q_{ex} - Q_{in} &= m_m c_m \frac{dt_m}{d\tau}
\end{align*}
$$

In formulas, $\tau$ Time; $\xi$ is the pressure loss coefficient, $\alpha_ex$ is the convection heat transfer coefficient; $k_n$ is the convection heat transfer coefficient between the working medium in the pipe and the pipe wall; $t_2$ is the outlet temperature of the working medium in the pipe; $n$ is the index, usually taken as 0.8; $D_g$ is the mass flow of flue gas outside the pipe; $K$ is the correction coefficient of flue gas heat release; $c_1$ and $c_2$ are the specific heat at the inlet and the specific heat at the outlet respectively; $C_m$ is the specific heat at the pipe wall.

The linearization of Formula (1) and the Laplace transform are carried out. The superheater inlet steam flow rate and heat flow rate change are small, which can be ignored in dynamic simulation. The outlet steam temperature is mainly affected by the inlet steam temperature change [15]. Therefore, the transfer function between the simplified steam temperature at the inlet of superheater and the steam temperature at the outlet of superheater is shown in Figure 2.

In Figure 2, $K_1 = \frac{c_1}{c_2}$; $T_i = \frac{m_m c_m}{5D_c c_p}$; CP is the outlet of Desuperheater Specific heat capacity at constant pressure.

Under different load levels, the steam temperature at the inlet and outlet of the superheater changes little, so $K_1$ is close to 1 as it is the c ratio of flue gas inlet vs outlet, which does not change much; $T_i$ is related to the mass, specific heat, steam flow and specific heat at constant pressure of the metal on the tube wall of the superheater. Due to the relatively small change of other relevant parameters, when the load increases, $D_i$ increases, thus $T_i$ decreases.

**Figure 1.** Superheater lumped parameter model.  
**Figure 2.** Superheater model.
2.1.2. Model of spray desuperheating section. Spray desuperheating process is to spray desuperheating water after atomization directly into superheated steam generated by superheater [1], as shown in Figure 3, spray desuperheating is a heat exchange process of two-phase mixing, which shall meet energy conservation and mass conservation.

In Figure 3, \( D_0 \) is the inlet steam mass flow; \( D_W \) is the inlet desuperheating water mass flow; \( D \) is the outlet steam mass flow; \( h_W, h_0 \) and \( h \) are the inlet desuperheating water specific enthalpy, the inlet steam specific enthalpy and the outlet steam specific enthalpy respectively; \( t_W \) and \( t_0 \) are the inlet desuperheating water temperature and the inlet steam temperature respectively.

\[
\begin{align*}
V \frac{d\rho}{d\tau} &= D_x + D_w - D \\
V \frac{d(p\rho h)}{d\tau} &= D_x h_x + D_w h_w - Dh \\
\frac{c_w m_w}{D_w} \frac{dt_w}{d\tau} &= Q_w - Q_x \\
Q_x &= D_x (h_x - h) \\
Q_w &= D_w (h - h_w)
\end{align*}
\]

In Formula (2), \( V \) is the volume of spray desuperheater; \( \rho \) is the density of outlet steam; \( t_m, c_m, m_m \) and \( Q_o \) are the average wall temperature, specific heat capacity of wall, metal mass of wall and heat release of steam in unit time; \( Q_W \) is the heat absorption of desuperheating water in unit time.

Linearize Equation (2) and use Laplace transform to simplify the transfer function model of spray desuperheater after treatment, as shown in Figure 4.

In Figure 4, \( K_2 = \frac{h_0 - h_w}{D c} \), \( K_2 \) is related to the specific enthalpy of the steam at the inlet of the desuperheater, the specific enthalpy of the desuperheater, the steam flow at the outlet of the desuperheater and the specific heat capacity of the steam at the constant pressure at the outlet of the desuperheater; \( T_2 = 0.5 \frac{m_o c_m}{D c} \), \( T_2 \) is related to the mass of metal wall, specific heat of Desuperheater pipe, steam flow at desuperheater outlet and specific heat capacity at constant pressure.

![Figure 3. Lumped parameter model of water spray desuperheater.](image)

![Figure 4. Model of water spray desuperheater.](image)

2.2. Turbine model considering boiler influence

2.2.1. Once through boiler model. The once through boiler model is shown in Figure 5. According to the principle of energy balance and mass balance, the fuel quantity and feed water of the boiler are properly proportioned to make the heat of the feed water entering the evaporator meet the requirements of the normal operation of the boiler [13].

In Figure 5, \( U_W \) is the water supply and \( U_b \) is the coal supply; \( Ta \) is the delay time of fuel heat release; \( H_{wb} \) is the gain of water supply flow; \( K_{eva} \) is the gain of heat release; \( T_{eva} \) is the delay time of steam in evaporator; \( H_{eva} \) is the gain of steam flow out of evaporator; \( T_i \) is the delay time of steam flowing through superheater and other pipes; \( K_a, K_b \) and \( K_C \) are the proportion coefficient.
2.2.2. Turbine model. The turbine model is shown in Figure 6. A natural power overshoot coefficient of high pressure cylinder is introduced to reflect the physical phenomenon that the output proportional coefficient of high pressure cylinder in the dynamic process is larger than that in the steady state when the regulating valve suddenly opens.

In Figure 6, \(F_{HP}, F_{IP}, F_{LP}\) is the power ratio of high, medium and low pressure cylinders respectively [17], and \(F_{HP} + F_{IP} + F_{LP} = 1\), \(T_{CH}\) is the steam volume time constant; \(T_{RH}\) is reheater time constant; \(T_{CO}\) is the crossover valve time constant.

By combining Figure 5 with Figure 6, a turbine model considering the influence of boiler is established.

![Figure 5. Once-through boiler model.](image)

![Figure 6. Steam turbine model.](image)

2.2.3. Model of turbine speed control system considering spray desuperheating system. Combining the above-mentioned spray desuperheating system model with the steam turbine model considering the influence of boiler, the boiler turbine system simulation model is established, and its structure is shown in Figure 7.

In Figure 7, feed water and coal are adjusted at an appropriate rate to ensure material conservation and energy conservation, so as to stabilize steam pressure and steam temperature. After the given value is determined, the deviation is sent to the regulator for calculation according to the system feedback signal, and then the instruction is given to the actuator. When the system frequency changes, the speed of the grid connected generator will change. Generally speaking, the turbine regulating system will work, change the steam inflow of the turbine, and adjust the output power of the generator to meet the needs of the load.
3. Simulation analysis

3.1. Simulation analysis of spray desuperheating system

The simulation model of thermal power unit is established in MATLAB SIMLINK. Taking the spray desuperheating system of a power plant as an example, \( P_1=25\text{MPa}, t_1=460^\circ\text{C}, h_1=3000\text{kJ/kg}, D_1=200\text{kg/s}, D_g=10000\text{kg/s}, t_1=1000^\circ\text{C}, h_w=1000\text{kJ/kg}, t_w=200^\circ\text{C}, D_w=30\text{kg/s} \).

(1) Simulation of desuperheating water disturbance

This article uses simulink simulation software for simulation. At 20s, the desuperheating water flow is reduced from 30kg/s step to 15kg/s, and other inputs remain unchanged. The simulation and measurement results are shown in Figure 8.

\[ \text{Figure 7. Boiler-turbine system simulation model.} \]

\[ \text{Figure 8. Variation curve of outlet steam parameters with desuperheating water flow rate.} \]
Figure 8 shows that the simulation result and the actual measurement data change process and steady state value are roughly the same, indicating that the established spray desuperheating system model is accurate and effective. Generally speaking, when the flow of desuperheating water decreases, the enthalpy and temperature of outlet steam increase, the flow of outlet steam decreases, and the temperature and enthalpy of outlet steam can be stabilized again within 20s.

3.2. Simulation analysis of operation characteristics of steam turbine system considering the influence of boiler

The single reheat steam turbine model considering the influence of boiler formed in combination of Figure 5 and Figure 6 is respectively simulated in the upper load step and the lower load step, and compared with the measured results and original simulation results without considering the influence of boiler, as shown in Figure 9.

As can be seen from Figure 9, after the step command is issued on the load, the electromagnetic power is increased, and the main steam pressure is decreased; after the step command is issued, the electromagnetic power is decreased, and the main steam pressure is increased. The simulation curve obtained from the steam turbine model considering the influence of the boiler is close to the measured curve, which can more accurately reflect the mid-to-long-term operating characteristics of the thermal power unit. To sum up, it is necessary to consider the influence of the boiler on the dynamic response of the unit in the long-term stability analysis.

3.3. Simulation analysis of influence of spray desuperheating system on dynamic characteristics of steam turbine system

Based on Figure 7, a boiler turbine system model is established, and its dynamic response characteristics are simulated and analyzed.

(1) Speed step disturbance

The given value of turbine speed changes from 0.8 to 0.85, 0.9 and 0.95 respectively, and the dynamic response simulation results are shown in Figure 10.

It can be seen from Figure 10 that when the given speed changes, the main steam flow will be adjusted to the required value within a certain period of time, so as to regulate the output power and speed of the turbine at a faster speed, and finally meet the demand.

(2) Desuperheating water flow disturbance

Set the flow of desuperheating water to reduce by 20%, 40% and 60% respectively, and other inputs have not changed. The dynamic response of the system is shown in Figure 11.

It can be seen from Figure 11 that when the desuperheating water flow is greatly reduced, the main steam flow will be correspondingly reduced, but the reduction is not significant. The spray desuperheating system has little influence on the main steam parameters, so it can only adjust and
control the main steam accurately in a certain range. The spray desuperheating system can describe the action characteristics of the main steam and power regulation process, which plays an important role in improving the accuracy of the simulation of the influence of thermal equipment on the power grid.

![Main steam flow](image1)

![Electromagnetic Power](image2)

![Rotation rate](image3)

**Figure 10.** Dynamic response of steam turbine with step disturbance at speed.

![Main steam flow](image4)

![Electromagnetic Power](image5)

![Rotation rate](image6)

**Figure 11.** Dynamic response of steam turbine when desuperheating water flow rate changes.
4. Conclusions
(1) The model of steam turbine system with spray desuperheater and boiler can reflect the dynamic characteristics of thermal system, and can also be applied to the dynamic stability simulation analysis of power system, with better simulation effect.
(2) The spray desuperheater has little influence on the main steam parameters, but it plays an important role in improving the accuracy of the overall simulation of the thermal system, and helps to reveal some phenomena that are difficult to explain in the isolated modeling environment of the steam turbine unit.
(3) The boiler system has a great influence on the main steam flow and pressure. It is also necessary to consider the influence of boiler on the dynamic response of the unit in the large disturbance and medium and long term simulation analysis of power system.

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