Transient simulation model and process simulation analysis of fast cut back process in thermal power plant

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Abstract. Fast Cut Back (FCB) technology of large thermal power plant can maintain the isolated operation of auxiliary power after the units are disconnected from the power grid. FCB unit can immediately cut off all external loads without turbine or boiler shutdown in case of large power grid failure, and supply power immediately as the external power grid fault eliminated, which has a very important impact on improving the stability and the recovery speed of the power grid system. Therefore, it is necessary to establish a dynamic mathematical model of thermal power plant to simulate FCB process. According to the principle of mass and energy balance, a dynamic mathematical model of 1050 MW thermal power unit was established. The model considered the change trends of main steam pressure and temperature caused by the action of main steam valve and high-pressure (HP) bypass valve in FCB process, and the action characteristics of safety valve and pressure control valve (PCV) valve in FCB system. This model provides a reference for the simulation and control of FCB process in thermal power unit.

1. Introduction
With the continuous expansion scale and increasing complexity of power system, it is necessary to consider the system recovery capacity after blackout in the process of power grid construction and operation maintenance. The system stability and system recovery speed are the most important criteria to judge the recovery ability. The recovery speed of power system is related to the total capacity of the units with black start capability in the system. Fast Cut Back (FCB) technology of thermal power plant can maintain the isolated operation under auxiliary power after the units are disconnected from the power grid. In case of large power grid failure, FCB unit can immediately cut off all external loads without turbine or boiler shutdown. As the fault of external power grid is eliminated, the units can supply power to the power grid immediately. This advantage makes the thermal power unit with FCB function can be used as a large capacity black start power supply, which greatly shortens the system recovery time and improves the system recovery speed after the blackout.

Generally, it takes about 10 hours for the thermal power unit to restart after shutdown (the specific situation varies with the unit capacity and other factors), and the external power supply is required to provide auxiliary power for the unit restarting[1]. Therefore, if its not equipped with high-power diesel generator, the general thermal power unit is difficult to be used as black start power supply. However,
due to the limitation of diesel engine power, the capacity of thermal power unit which can start by diesel engine with auxiliary power is small and the ability of starting system is weak. In the power grid with thermal power units as the main generating units, FCB units play an important role in black start, which is mainly reflected in the following aspects: (1) Reduce outage time and economic losses. If most of the thermal power units have FCB function, all thermal power units can immediately supply power to the power grid, and the whole power grid will resume power supply in the shortest time\cite{2}. (2) Reduce unit damage and prolong unit life. The unit without FCB function will have main fuel trip (MFT) when system is disconnected. The metal stress change amplitude and frequency of the unit are greater than that of the FCB unit, and the equipment life damage is more serious. For the units that can successfully enter the FCB state, the thermal parameters of the unit, especially the boiler system, will operate within the design allowable range, which can reduce the equipment loss and prolong the service life compared with MFT\cite{3}. (3) Reduce unit start-up costs. After MFT shutdown, the conventional unit needs to be flushed, working medium replenished, boiler oil burning, steam channel preheating and other steps during restart, so the start-up cost is very expensive. When the FCB unit enters the FCB condition and then supplies power to the power grid again, it belongs to warm start, which can be understood as the load increase of the unit under normal operation. In this process, the cost is only a small amount steam loss during FCB process\cite{4}. Compared with units full shutdown, FCB function can greatly reduce the start-up cost of units from grid disconnection to power supply restoration.

At present, modeling technology is an effective method to study FCB, but there is little research on it. In order to solve these problems, a dynamic mathematical model of FCB simulation in thermal power plant was established and verified by FCB process of 1050 MW unit from 100% turbine maximum continuous rating (TMCR) to 50% boiler maximum continuous rating (BMCR) condition. The result shows that the model is correct and reliable, which provides model simulation method for further FCB control optimization.

2. System composition of thermal power plant

2.1. Overview of thermal power plant
The thermal power plant is located in Kramatwatu, Serang Regent District, Bantan Province, Indonesia. In the first phase of this project, 2×1050 MW ultra supercritical coal-fired power generation units will be constructed. The average annual utilization hours of the unit in this project is 7533 h, the net capacity of power supply is about 2×991 MW, and the utilization rate is 86%. Figure 1 shows the structure diagram of thermal power plant.

2.2. Key parameters of FCB system

2.2.1. Key performance parameters of boiler
The boiler in the FCB system of the unit adopts the ultra supercritical parameter variable pressure direct current type produced by Beijing Bawei boiler manufacturer. The boiler structure is all steel frame and full suspension II style, adopts balanced ventilation, solid slag discharge, and the thermal system is designed as a reheat system with full outdoor layout. Under BMCR conditions, the maximum continuous evaporation capacity is 3100 t·h⁻¹, and the boiler outlet steam parameters are 28.35 MPa(a), 605/603 ℃. The design and manufacture standard of Bawei boiler is American ASME standard. Safety relief valve with 100% capacity is set on superheater and reheat steam system. The boiler superheater is equipped with PCV valves with 40% BMCR capacity and 300 t·h⁻¹ controllable relief valves are set at reheater inlet.

2.2.2. Key performance parameters of steam turbine
The steam turbine configured in FCB system of the unit is N1055/27/600/600 steam turbine produced by Shanghai steam turbine Co., Ltd., adopting Siemens technical system, high and medium pressure
combined start-up, ultra supercritical, primary intermediate reheat, single shaft, double back pressure, four cylinder and four exhaust. The steam turbine adopts the constant-sliding-constant operation mode. The key parameters of the steam turbine were shown in Table 1.

![Figure 1. Structure diagram of thermal power plant.](image)

| Item                                | Parameters       |
|-------------------------------------|------------------|
| Rated power                         | 1055 MW          |
| Valve fully open power              | 1092.9 MW        |
| Rated main steam valve front pressure | 27 MPa           |
| Rated temperature in front of main steam valve | 600 ℃          |
| Rated temperature in front of reheat steam valve | 600 ℃          |
| Exhaust temperature of HP cylinder  | 372.3 ℃          |
| Exhaust pressure of HP cylinder     | 6.397 MPa        |

3. Modeling and Simulation of FCB process

3.1. FCB process control strategy
Before FCB occurs, the unit operated at rated loads. At this time, the parameters of boiler outlet and turbine inlet were rated. The high pressure (HP) and low pressure (LP) bypass valves were closed, and
the extraction steam regenerative system was in normal operation with the balance of steam and water. When FCB started, the following control occurred.

The coal mills quickly reduced the coal feeding rate of the boiler from 510 \text{t·h}^{-1} to 181 \text{t·h}^{-1}, and the operating pulverizing system reduced from 6 sets to 3 sets. This was conducive to stable boiler combustion in the process of rapid reduction of combustion rate. At the same time, to prevent the reheat steam temperature from being disturbed during FCB, 6 PCV valves opened and the spray water stop valve of reheat desuperheating closed. The HP and LP bypass valves fully opened within 3 s, and water was sprayed to desuperheating. After receiving the FCB signal, the HP bypass valve quickly adjusted the main steam pressure to the system pressure set at about 19 MPa and kept the pressure unchanged. The LP bypass automatically switched to the constant pressure mode after the FCB signal sending, cooperated with combustion adjustment, and finally maintained the outlet pressure of LP bypass at 1.7 ~ 2.5 MPa. The turbine overspeed control (OPC) acted quickly to balance the speed rise of steam turbine. Except No.2 HP heater continuing to operate, other HP and LP heaters were shut down. The heating steam source of deaerator was quickly switched to auxiliary steam system after depressurization of cold reheat steam.

3.2. Mathematical model of FCB unit system

During FCB process, after the HP bypass valve acting, the superheated steam at the outlet of main steam system entered into HP turbine and HP bypass, respectively. The steam mass and energy balance equations were as following\cite{5}.

\begin{equation}
V_{\text{sp}} \frac{d\rho_{\text{sp}}}{dt} = D_{\text{sp}} + D_{\text{sw}} - D_{\text{st}} - D_{\text{HPbp}} \tag{1}
\end{equation}

\begin{equation}
V_{\text{sp}} \frac{d\rho_{\text{sp}} h_{\text{sp}}}{dt} = D_{\text{sp}} h_{\text{st}} + D_{\text{sw}} h_{\text{dw}} + Q_{\text{sp}} - D_{\text{st}} h_{\text{sp}} - D_{\text{HPbp}} h_{\text{sp}} \tag{2}
\end{equation}

The steam mass flow rate of HP turbine (HPT) inlet\cite{6} was

\begin{equation}
D_{\text{st}} = \mu_{\text{st}} \kappa_{\text{HPT}} \sqrt{\frac{P^2_{\text{st}} - P^2_{\text{les}}}{T_{\text{av}}}} \tag{3}
\end{equation}

The inlet and outlet flow rates of the reheater were

\begin{equation}
D_{\text{rh\_in}} = D_{\text{HPbp}} + D_{\text{HPbp\_dw}} + Q_{\text{HPT\_out}} - D_{\text{d}} \tag{4}
\end{equation}

\begin{equation}
D_{\text{rh\_out}} = D_{\text{LPbp}} + Q_{\text{IPT\_in}} \tag{5}
\end{equation}

HP bypass valve was connected to the main steam system, and its flow rate mostly depended on the main steam properties and valve opening\cite{5}, it was calculated as

\begin{equation}
D_{\text{HPbp}} = 0.01 \cdot f_1(\mu_{\text{HPbp}}) \cdot f_2(p_r) \cdot \sqrt{T_0/T_M} \tag{6}
\end{equation}

The inlet flow rate of intermediate pressure turbine (IPT)\cite{7} was

\begin{equation}
D_{\text{IPT\_in}} = \mu_{\text{IPT}} \kappa_{\text{IPT}} \sqrt{\frac{P^2_{\text{rh}} - P^2_{\text{les}}}{T_{\text{rh}}}} \tag{7}
\end{equation}

During the process of FCB, the outlet flow rate of LP bypass valve was calculated in an approximate method, as equation (8), considering the great pressure difference between the reheater and condenser. The reheated steam heat capacity was pertinent to the inlet flow, as exhibited in equation (9)\cite{8}.

\begin{equation}
D_{\text{LPbp}} = \mu_{\text{LPbp}} \cdot \kappa_{\text{LPbp}} \cdot P_r \tag{8}
\end{equation}

\begin{equation}
Q_{\text{rh}} = 1000 \cdot D_{\text{rh\_in}} \cdot \beta_{\text{rh}} \tag{9}
\end{equation}

The power of HP, IP and LP turbine were

\begin{equation}
W_{\text{HPT}} = \eta_{\text{HPT}} \cdot (D_{\text{HPT\_in}} h_{\text{HPT\_in}} - D_{\text{les}} h_{\text{les}} - D_{\text{HPT\_out}} h_{\text{HPT\_out}}) \tag{10}
\end{equation}
Steam source of deaerator system was switched to cold reheat steam during FCB, with the 4th steam extraction of turbine was shut down. The mass and energy balance equations were

\[ W_{hL} = \eta_{hL} \left( D_{hP} - D_{hE} - D_{hS} - D_{hD} - D_{hT} - D_{hG} - D_{hF} - D_{hR} - D_{hI} - D_{hO} \right) \]

Steam source of deaerator system was switched to cold reheat steam during FCB, with the 4th steam extraction of turbine was shut down. The mass and energy balance equations were

\[ V_{h} \frac{d\rho_{h}}{dt} = D_{hI} - D_{hO} \]

\[ V_{h} \frac{d\rho_{h}}{dt} = D_{hP} + D_{hL} + D_{hT} - D_{hO} - D_{hI} - D_{hF} \]

where \( D \) for flow rate (kg/s), \( \rho \) for pressure (MPa), \( T \) for temperature (℃), \( V \) for volume (m³), \( \rho \) for density (kg/m³), \( Q \) for heat exchange (kJ/s), \( h \) for enthalpy (kJ/kg), \( W \) for power (kW), \( t \) for time (s), \( \mu \) for valve opening (%), \( \text{sp} \) for superheated steam, \( \text{ds} \) for desuperheating water, \( \text{st} \) for steam turbine, \( \text{HPbp} \) for HP bypass, \( \text{ss} \) for saturation steam, \( \text{rh} \) for reheater, \( \text{ms} \) for main steam, and \( \text{es} \) for extraction steam.

### 3.3. Simulation of FCB process

The unit operated under 100% TMCR loads initially, the main steam valve and HP bypass valve acted rapidly after FCB process starting, as shown in Figure 2. The main steam valve started to close quickly at 0s, then slowly re-opened within 1 s to Kv value at 50% BMCR loads and remained stable. At the same time, the HP bypass valve was opened for 3 s. Both the action curves of main steam valve and HP bypass valve were determined according to the design data. According to the valve Kv value, the main steam and bypass steam mass flow rates were calculated, and the flow changes were shown in Figure 3. After entering FCB conditions, the change trend of main steam pressure and temperature were exhibited in Figure 4. Both pressure and temperature increased rapidly and then decrease to stabilization. The main steam pressure raised from 27 MPa under 100% TMCR loads to the maximum value of 34.28 MPa at 0.46 s, and then began to reduce fast. At about 1.48 s, the pressure dropped to the lowest point at about 12.77 MPa, and then began to vibrate and stabilized gradually. The main steam temperature increased rapidly from 600 ℃ under 100% TMCR loads to 607.14 ℃ under 50% BMCR loads, which was obtained at 1.26 s, then began to decline slowly and reached stable at around 583.36 ℃ after 3 s. The fluctuation of temperature obviously lagged behind that of pressure, and the fluctuation range of temperature was far less than that of pressure. The operation process of safety valves and PCV valves in FCB process was also simulated. It was found that the safety valves were always closed during the transition from 100% TMCR loads to 50% BMCR loads. Meanwhile, the PCV valves were opened at 0.25 s and closed at 0.68 s. The actions of safety valves and PCV valves during loads operation process satisfied and realized the design requirements of FCB function of the unit.

![Figure 2](image2.png)

**Figure 2.** Kv values of main steam valve and HP bypass valve in FCB process.

![Figure 3](image3.png)

**Figure 3.** Variation of main steam pressure and temperature in FCB process.
4. Conclusions
Based on the data analysis and the balance of mass and energy, the dynamic FCB process mathematical model of thermal power plant was established. The transient parameters of main steam of 1050 MW thermal power unit switching from 100% TMCR loads to 50% BMCR loads during FCB process was simulated. The results showed that the proposed model could accurately simulate the dynamic characteristics of FCB conditions, and the simulation results were consistent with the engineering design results. The successful implementation of FCB dynamic simulation calculation function could be used for simulation under different working conditions and discussion of FCB process control strategy. It provides a reference for optimizing and controlling FCB process of thermal power unit.

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