Test and simulation of primary frequency regulation of 600MW sub-critical thermal power units with wide load operation

Chunlei Zhang1*, Longfei Zhu1, Dahai Yu2, Paiyou Si1, Shuangbai Liu1, Long Mei1, Ting Zhao1, Jing Zhang3, Tao Zhang3 and Yuou Hu3

1 North China Electric Power Research Institute Co. Ltd., Beijing, 100045, China
2 China Electric Power Research Institute, Beijing, 100192, China
3 North China Branch of State Grid Corporation of China, Beijing, 100053, China
*Corresponding author’s e-mail: zhangchunleixny@126.com

Abstract. To reveal the performance of primary frequency regulation of the 600MW sub-critical thermal power units in a wide load range and accurately simulate the process, the primary frequency regulation performance of a 600MW sub-critical thermal power unit was studied with a wide load ranging from 20% to 90% under rated conditions. The model of steam turbine in BPA was modified in consideration of steam pressure and the valve throttling effect. The primary frequency regulation performance of the unit was simulated with the modified model. The research results show that the primary frequency regulation performance of the thermal power unit is poor at low load and the results of simulation with the modified model are highly consistent with the tested data due to consideration of steam pressure and valve throttling effect, meaning that the model can be used to simulate the primary frequency regulation of the thermal power unit with wide load operation accurately.

1. Introduction
In the future, thermal power units will play an increasingly prominent role in the peak regulation of power system [1-3]. When units are running at strongly-varied loads, their operating parameters such as steam pressure also vary greatly. Accordingly, the performance of primary frequency regulation varies as well [4-6]. To ensure the safe and stable operation of the power grid, it is necessary to accurately grasp the response characteristics of primary frequency regulation under different loads, and it is also necessary to study and accurately simulate the process of primary frequency regulation under a wide load range.

Currently, there have been many studies on the primary frequency regulation of thermal power units. Literature [7] presented a control system optimization scheme for a 1000 MW supercritical thermal power unit and investigated the characteristics of primary frequency regulation of the unit running at 50% ~ 100% of rated load. In literature [8], the classical PID controller was optimized and the simulation study was conducted for the primary frequency regulation of a 600 MW supercritical thermal power unit running at 30% ~ 100% of rated load. In literature [9], an improved swarm optimization algorithm was proposed for the identification of simulation model parameters of coal-fired units under deep peak load regulation, and the effectiveness of the improved algorithm was verified by simulating the primary frequency regulation of a 660 MW thermal power unit at 240 MW
load, using model parameters obtained from an improved algorithm. Literature [10] presented an optimization scheme for the control system of a 330 MW sub-critical thermal power unit and the performance of primary frequency regulation under low load was tested and verified. In literature [11], the model of the speed control system of thermal power units was improved considering the effect of main steam pressure, which was verified using measured data of 1000 MW thermal power units running at 80% of rated load. However, there are no published empirical and simulation studies on the primary frequency regulation of 600MW sub-critical thermal power units operating at wide load.

To grasp and simulate the performance of primary frequency regulation of the units, this paper conducted an experimental study, taking the units running at 20%~90% of rated load as research subject. The turbine model in the BPA was then improved by considering the effects of steam pressure and throttling valves on the power response characteristics. Finally, a simulation study was conducted for primary frequency regulation based on the improved model. The results show that the lower the operating load is, the worse the performance of primary frequency regulation is. Meanwhile, the identification and simulation results of the improved model match well with the measured data because the influence of the operating parameters is taken into account.

2. Overview of the unit

The unit is a 600MW sub-critical coal-fired generating unit. The turbine model is N600-16.7/538/538, which is a sub-critical, single-shaft, once-intermediate reheat, three-cylinder, four-exhaust steam, and direct air-cooled condensing steam turbine. The boiler model is SG2059/17.5-M915 and it is a π-type drum boiler with sub-critical parameters, controlled circulation and primary intermediate reheat.

The primary frequency regulation of the unit was realized through the feed-forward link and PID link together. Its architecture is shown in figure 1. When the frequency difference was input, the power variation was output by calculating with the parameters of the primary frequency regulation, and then the new power setting value was calculated. The feed-forward and the PID controller work together to achieve fast and accurate power regulation of the unit.

The primary frequency regulation sets the dead zone of frequency difference as well as the limit of its power variation, as shown in figure 2. To improve the stability of operation under low load, the primary frequency regulation parameters of the unit below 50% of the rated load are set smaller, as shown in table 1.

| Loads of the unit (MW) | Modified coefficient of power variation | Limits of power variation (MW) |
|-----------------------|----------------------------------------|--------------------------------|
| 300                   | 1                                      | ±36                            |
| 240                   | 1                                      | ±20                            |
| 180                   | 0.7                                    | ±15                            |
| 120                   | 0.6                                    | ±0                             |
| 119                   | 0                                      | ±0                             |
3. Experimental study

A frequency regulation test was performed on the unit at a wide load (20% ~ 90% of rated load), and its power response characteristics were studied.

3.1. Status of the unit before the test

When the unit is operated at different loads, its main steam pressure and the position of regulating valve show significant differences, as shown in figure 3 and figure 4. As can be seen from the figures, the main steam pressure is 10.9 MPa and 15.4 MPa at 20% and 90% of rated load, respectively, and the position of the integrated valves is 20% and 84%, respectively. The main steam pressure affects the steam pressure in front of the regulating valve, and the position of the regulating valve affects its throttling effect. Both of these will affect the power response, leading to significantly different characteristics at various operating loads.
3.2. Experimental results and analysis

A primary frequency regulation test with a disturbance of +0.1Hz was carried out at 90%, 75%, 60%, 40%, 30% and 20% of the rated load respectively. The measured results show that the response characteristics of primary frequency regulation under each test load show large differences, as shown in figure 5 and figure 6. It can be seen from the figures that the lower the operating load is, the lower the power response speed is and so is the amplitude. Figure 7 shows the power variation at each test load. As can be seen from the figures, for the 90% load test the power variation at 15s after the start of the test is about 16 MW. For the 40% load test it is about 12 MW, and for the 20% load test it is about 8.1 MW. The lower the load is, the smaller the variation is.

Figure 4. The position of control valve of the unit running at 20%–90% of rated load

Figure 5. The change of power of the unit running at 60%–90% of rated load during primary frequency regulation with frequency disturbance of +0.1Hz
Figure 6. The change of power of the unit running at 20%~40% of rated load during primary frequency regulation with frequency disturbance of +0.1Hz

Figure 7. The power variation of the unit running at 20%~90% of rated load during primary frequency regulation with frequency disturbance of +0.1Hz

The reason for this phenomenon is that the operating parameters such as steam pressure in front of the valve vary greatly under different operating loads, resulting in large differences in the power response characteristics. In the process of primary frequency regulation, the turbine output power mainly depends on the steam flow, while the steam flow is influenced by the combination of factors such as steam pressure in front of the valve, valve opening and valve throttling. Related studies have shown that the steam flow through the turbine regulating valve can be expressed as a function of steam pressure, valve opening and pressure ratio before and after the valve, as shown in equation (1) [12].

\[ G = 0.648(p_0 v_0)^{1/2} \beta_1 \chi F_v p_0' \]  

\[ \varepsilon_1 = \frac{p_0''}{p_0'} \]  

Equation (2)
\[
\beta_i = \left(1 - \frac{(\varepsilon_i - \varepsilon_r)^2}{(1 - \varepsilon_r)^2}\right)^{1/2}
\]

(3)

\[
\chi = f(\varepsilon_i, V)
\]

(4)

Where \( G \) refers to the steam flow of the regulating valve; \( P_0 \) is the steam pressure in front of the main steam valve of the unit; \( v_0 \) is the specific volume of steam in front of the main throttle valve of the unit; \( P_0' \) is the steam pressure in front of the regulating valve; \( P_0'' \) is the steam pressure behind the regulating valve; \( \varepsilon_r \) is the critical pressure ratio, and its value is 0.5457 for superheated steam; \( \beta_i \) is the peakmen coefficient of the regulating valve, and it is the function of \( \varepsilon_i \); \( \chi \) is the relative flow coefficient of the regulating valve and the function of \( \varepsilon_i \) and \( V \); \( F_i \) is the nominal flow area of the regulating valve.

Obviously, \( \beta_i \chi \) is a function of the pressure ratio \( \varepsilon_i \) and the opening of the regulating valve \( V \). Related studies have shown that \( \beta_i \chi \) is strongly negative correlated with the pressure ratio \( \varepsilon_i \) and positive correlated with the opening of the regulating valve \( V \) [12].

From equation (1), it can be seen that the regulating valve opening, steam pressure in front of the valve, regulating valve throttling effect and other factors have an important impact on the power response characteristics of the primary frequency regulation of the unit. The lower the steam pressure in front of the valve is, the smaller the power variation is [12]. For this unit, the main steam pressure was 15.4 MPa at 90% of rated load. However at 40% of rated load the main steam pressure was only 10.4 MPa with a decrease of 32%, resulting in a significant drop in the power variation of the primary frequency regulation.

4. Simulation study
To accurately simulate the power response of the unit with wide load operation, it is required that the simulation model can reflect its operating characteristics. However, the current BPA model has obvious shortcomings and needs to be improved.

4.1. The BPA model and its shortcomings
For simulation of the power response of the unit, calculation with BPA requires the regulation system model, the actuator model and the turbine model. The entire unit model is obtained by connecting the three models in sequence. For conventional single-reheat coal-fired units, the GJ model is usually selected as the regulation system model, the GA model as the actuator model, and the TB model as the turbine model. The structure of the TB model is shown in figure 8 [15].

In figure 8, \( P_{GV} \) is the regulating valve opening; \( T_{ch} \) is the time constant for the volume of the front chamber of the high pressure cylinder; \( T_{ch} \) is the time constant for the volume of the re-heater; \( T_{co} \) is the time constant for the volume of the low pressure connecting pipe chamber; \( \tilde{F}_{HP}, \tilde{F}_{MP} \) and \( \tilde{F}_{LP} \) are the percentage of power of high, medium and low cylinders respectively; \( \lambda \) is the natural overshoot coefficient of high-pressure cylinder power; \( P_M \) is the output power of the turbine.
From the theoretical analysis, the TB model cannot accurately describe the power response of the unit during primary frequency regulation. As can be seen from figure 8, the only input to the TB model is the regulating valve opening. However, according to equation (1), the factors that affect the steam flow through the valve also include the steam pressure in front of the valve and the pressure ratio.

From the analysis on simulation effect, the simulation results of the applied TB model cannot be fully matched with the measured power of the unit. On the one hand, the simulation was performed using the model parameters identified from the high-load test data, and the simulation results did not match well with the low-load measured data because the influence of steam pressure and other factors are not taken into account in the TB model, as shown in figure 9. On the other hand, the simulation results could not match the power surge at the beginning of the experiment, as shown in figure 10. In the actual experiment, once the primary frequency regulation was triggered, the valve opening changed abruptly, the high-pressure steam which was accumulated in front of the valve flowed rapidly, and the power of the unit surged. The TB model does not consider the effect of steam pressure and valve throttling on power. Thus the simulation results cannot reflect this phenomenon.

![Figure 9](image9.png)

**Figure 9. Simulation results of the primary frequency regulation of the unit at 40% of rated load in the BPA model**

![Figure 10](image10.png)

**Figure 10. Simulation results of the primary frequency regulation of the unit running at 75% of rated load in the BPA model**

4.2. Model improvement and application methods

To reflect the influence of the steam pressure in front of the valve and the throttling effect of the control valve on the power response of the unit, “energy storage coefficient” is added to the input of the conventional turbine model in consideration of the convenience in simulation. The improved model takes the product of the regulating valve opening and the energy storage coefficient as input, as shown in figure 11.

![Figure 11](image11.png)
In simulation, the model can be applied according to the rules-“first identified, then simulated”. Firstly, the storage coefficients and other model parameters were identified using the measured data under the test load; before simulating, the storage coefficients corresponding to the simulated load were calculated by combining the identified storage coefficients corresponding to each test load, and then all the identified model parameters were placed into the model for simulation. The whole process is shown in figure 12.

4.3. Identification results
The identification results show that the improved model can well describe the primary frequency regulation process of the unit under wide load. Figures 13 to 17 show the comparison of the identification results of primary frequency regulation with the measured data at 90%, 75%, 60%, 40% and 20% of rated loads. As can be seen from the figures, the identification results of the improved model applied to each test load match well with the measured data. It cannot only reflect the phenomenon that the power variation is small due to the low steam pressure under low load, but also reflect the power surge process in the initial stage of the test.

The characteristics of the energy storage coefficient curve obtained from the identification are consistent with the theoretical analysis. Figures 18 to 20 show the storage coefficient curves obtained...
from the identification at 75%, 40% and 20% of the rated load. It can be seen from the figures that the energy storage coefficient at 75% rated load is significantly higher than that at 40% and 20% of rated loads. At the same time, the energy storage coefficient at each load increases rapidly at the initial stage of the test and gradually decreases after reaching the peak. According to equation (1), the higher the steam pressure in front of the valve is, the greater the coefficient is. When the valve opening rapidly increases, the pressure ratio rapidly decreases, and the steam flow rapidly increases. Then the valve opening remains stable, and the steam pressure in front of the valve gradually decreases. This is consistent with the change process in which coefficient first increase and then decrease. The identified energy storage coefficient coincide with the theoretical analysis, which further justifies the introduction of “energy storage coefficient”.

Figure 13. Identification results of primary frequency regulation at 90% of rated load based on the improved model

Figure 14. Identification results of primary frequency regulation at 75% of rated load based on the improved model
Figure 15. Identification results of primary frequency regulation at 60% of rated load based on the improved model

Figure 16. Identification results of primary frequency regulation at 40% of rated load based on the improved model

Figure 17. Identification results of primary frequency regulation at 20% of rated load based on the improved model
Figure 18. The curve of energy storage coefficients identified for primary frequency regulation at 75\% of rated load

Figure 19. The curve of energy storage coefficients identified for primary frequency regulation at 40\% of rated load

Figure 20. The curve of energy storage coefficients identified for primary frequency regulation at 20\% of rated load
4.4. Results of simulation and prediction

The above study shows that the improved model can better describe the primary frequency regulation of the unit with wide load. Therefore, we can make full use of the storage coefficients obtained from the identification, calculate the energy storage coefficients corresponding to the simulated load, and make simulation and prediction of the primary frequency regulation under the simulated load, as shown in figure 12.

For the 600 MW sub-critical unit, the storage coefficient curves identified at 40% and 20% rated load were used to obtain the storage coefficient at 30% rated load by linear interpolation, as shown in table 2 and figure 21. Then this energy storage coefficient and other model parameters were placed into the model and the simulation of primary frequency regulation at 30% of rated loads was performed. The results show that the simulation results match well with the measured power, as shown in figure 22.

Table 2. Data points of the curve of energy storage coefficients at 30% of rated load

| Data points | 20% of rated load | 40% of rated load | 30% of rated load |
|-------------|-------------------|-------------------|-------------------|
| A           | (t₀⁺₀ , 1)        | (t₀ , 1)          | (t₀ , 1)          |
| B           | (t₀⁺₁ , 1.5)      | (t₀⁺₀.₅ , 1.8)    | (t₀⁺₀.₇₅ , 1.6₅)  |
| C           | (t₀⁺₃.₄ , 1.₃₉)   | (t₀⁺₁ , 1.₇₃)    | (t₀⁺₂.₂ , 1.₅₆)   |
| D           | (t₀⁺₃.₄ , 1.₃₉)   | (t₀⁺₅ , 1.₆₄)    | (t₀⁺₄.₂ , 1.₅₂)   |
| E           | (t₀⁺₉.₇ , 1.₉)    | (t₀⁺₉.₅ , 1.₈)   | (t₀⁺₉.₆ , 1.₈₅)   |
| F           | (t₀⁺₁₄.₇ , 1.₇)   | (t₀⁺₁₆.₅ , 1.₅₅) | (t₀⁺₁₅.₆ , 1.₆₃)  |
| G           | (t₀⁺₇₄.₇ , 1.₅)   | (t₀⁺₇₆ , 1.₄)    | (t₀⁺₇₅.₃₅ , 1.₄₅) |

*Note: t₀ is the start time of the test

Figure 21. Calculated energy storage coefficients for the simulation of primary frequency regulation at 30% of rated load
The above simulation results show that the improved model can more accurately describe the primary frequency regulation process of the unit, as the effects of steam pressure and valve throttling are taken into account. At the same time, according to the principle - “identification first, simulation later”, the improved model can be used to simulate the primary frequency regulation of the unit more accurately.

5. Conclusions
To grasp the performance of primary frequency regulation of the 600MW sub-critical thermal power unit running at wide load and achieve accurate simulation, this paper conducted an experimental study on the primary frequency regulation of a 600 MW sub-critical thermal power unit in the interval of 20%~90% of rated load. The results show that lower operating load with lower steam pressure will lead to worse performance of primary frequency regulation. Taking into account the effects of steam pressure and valve throttling on the power response characteristics, the turbine model in the BPA was improved by adding an “energy storage coefficient” at its input. The improved model was used to simulate the primary frequency regulation of the unit. The results show that the identification and simulation results of the improved model match well with the measured data. The improved model can be used to simulate the primary frequency regulation of the unit more accurately according to the principle - “identification first, simulation later”.

Acknowledgments
This paper is supported by a self-funded scientific and technological project of North China Electric Power Research Institute Co. Ltd. - Study on the Modeling Scheme of Grid-related Characteristics of Coal-fired Units for Deep Peak Regulation (No.: KJZ2020061).

References
[1] Hou, Y. T. Li, X. B. Liu, C. et al. (2018) Flexibility reform situation and technical application of thermal power units. Thermal Power Generation, 47(5): 8-13.
[2] Wang, M. G. Lyu, H. K. Li, J. (2019) Review on deep peak regulation of coal-fired generating units in Zhejiang province. Zhejiang Electric Power, 39(5): 90-97.
[3] Mou, C. H. Ju, W. P. Huang, J. S. et al. (2018) Review and prospect of technologies of enhancing the flexibility of thermal power units. Thermal Power Generation, 47(5): 1-7.
[4] Li, J. Bao, J. S. Li, L. et al. (2020) Experimental study on width sliding pressure operation optimization of 630MW subcritical unit. Turbine Technology, 62(2): 147-150.
[5] Huang, X. C. Xu, X. Tan, R. et al. (2016) Optimization of sliding pressure operation test for 350 MW supercritical steam turbines. Power Equipment, 30(6): 382-385.
[6] Bao, W. W. Gao, F. F. Liu, Y. B. et al. (2016) Calculation method for optimum design of sliding
pressure operation curve of steam turbine. Zhejiang Electric Power, 35(3): 40-44, 59.

[7] Li, J. J. Yao, Y. Hu, S. Y. et al. (2020) Key technology and application of wide load frequency modulation and peak shaving control for supercritical units. Northeast Electric Power Technology, 41(12): 1-4.

[8] Zhang, B. Yue, L. Li, L. et al. (2021) Precise control of PFM for coal-fired units with wide load operations. Hubei Electric Power, 45(3): 110-114.

[9] Yu, G. Q. Cui, X. B. Shi, Y. Y. et al. (2020) Primary frequency regulation modeling of deep peak regulation unit based on improved group optimization algorithm. Electric Power, 53(6): 147-152.

[10] Li, L. Liu, X. P. (2020) Control strategy optimization for thermal power unit adapted to deep peak shaving for large-scale new energy source integration. Electric Power, 53(1): 155-161.

[11] Gu, Z. H. Bao, J. S. Zhang, B et al. (2019) Analysis and improvement of speed governor model considering the main steam pressure influences. Electric Power, 49(9): 93-98.

[12] Zhang, H. F. Xu, J. Q. Sun, Y. Y. et al. (2019) Characteristic model of combined governing valve and governing stage and optimization of steam distribution of steam turbine. Journal of Mechanical Engineering, 55(18): 165-172.

[13] Gui, Y. S. Shen, C. Q. Chen, H. L. et al. (2017) Research and optimization on primary frequency regulation characteristics with large frequency deviation for coal-fired power plants. Electric Power, 50(4): 106-112.

[14] Wang, G. Hao, T. Zhang, J. N. et al. (2014) Analysis on influencing factors of passing rate of primary frequency regulation of thermal power units. Electric Power, 47(2): 23-26.

[15] China Electricity Council. (2019) Guide for modeling and testing of generator’s prime mover and governor: DL/T1235-2019. China Electric Power Press, Beijing.