Modeling technology of large-scale half speed unit and its thermal actuator participating in grid frequency modulation

Libin Wen
Electric Power Research Institute of Guangxi Power Grid Co., Ltd., Nanning 530023, Guangxi, China
Email: 854661004@qq.com

Abstract. In view of the shortage of the technology of large half speed units in nuclear power participating in the primary frequency regulation modeling and parameter measurement of power grid, the speed regulation system, thermal actuator and prime mover model of nuclear power unit are established. At the same time, the technology of model parameter test, identification and verification is developed. The developed technology meets the requirements of BPA. Through the frequency step simulation of the established model and the obtained model parameters, and compared with the field test results, the results show that the model and its parameter test method are correct. The established model and its parameters can accurately reflect the dynamic process of nuclear motor group participating in the primary frequency modulation of large power grid.

1. Introduction
At present, with the rapid development of nuclear power, the installed capacity continues to increase. However, due to various reasons, nuclear power units in China always operate in the basic load mode and do not participate in frequency modulation, which has a huge impact on the control of grid frequency [1]. There are a lot of researches on primary frequency regulation of thermal power units in China, but there is a serious lack of researches on primary frequency regulation of large half speed units in nuclear power, which is related to the fact that nuclear power units seldom participate in grid frequency regulation. In reference [2], the simulation study of nuclear power units participating in primary frequency regulation is carried out under the isolated power grid with only nuclear power units. Its mathematical model is developed with FORTRAN language. The dynamic link library formed is embedded in Matlab/ Simulink in the way of S-function to realize the simulation. The actual test data of units are not given in this document. There are few literatures about the modeling technology of primary frequency modulation, model parameter test identification and accurate simulation of nuclear motor group, some of which are limited to model research [3] [4], safety [5] [6] [7] [8], peak regulation [9] [10]. Based on the primary frequency regulation characteristics of a 1000 MW nuclear power unit in Guangxi, the primary frequency regulation modeling, model parameter testing and identification, simulation analysis and field test of the nuclear power unit are carried out. The proposed modeling technology and simulation analysis method meet the requirements of BPA. The function of large half speed units in nuclear power participating in primary frequency regulation of power grid is realized through theoretical and field test research. The modeling technology and simulation method developed can accurately simulate the dynamic process of primary frequency regulation of nuclear power generating units.
2. Composition of nuclear power unit frequency modulation equipment

The frequency control equipment of nuclear power unit is mainly composed of speed control system, thermal actuator, prime mover and generator. When the primary frequency control function of the unit is put into operation, the speed control system receives the frequency signal of the power grid. When the difference between the grid frequency and the reference set value (frequency difference) of the unit frequency modulation speed exceeds the dead zone, the output command of the speed regulation system makes the thermal actuator act, the output of the prime mover changes, and the input power of the generator to the grid changes accordingly, so as to maintain the stability of the grid frequency.

3. Governing system model and parameters

3.1. Primary frequency control logic and modeling

The power closed-loop control operation mode of the nuclear power unit studied has the function of primary frequency modulation: when the frequency difference exceeds the dead zone, the frequency difference signal is divided into two channels, one channel is directly superposed on the opening instruction of the control gate through the frequency difference feed-forward, the other channel is superposed on the operator load instruction through the calculated value $\Delta P$ of the frequency difference power function, and the two channels of signal jointly ensure the rapidity and stability of primary frequency modulation. The primary frequency control logic is shown in Figure 1. The primary frequency control logic conforms to the BPA regulation system model (GJ/GJ +), as shown in Figure 2. The frequency difference power function is shown in Figure 3.

![Figure 1. Primary frequency control logic.](image1)

![Figure 2. Control model of speed control system (GJ/GJ +).](image2)

![Figure 3. Relation function between frequency difference and power.](image3)
3.2. Model parameter calculation of regulation system

3.2.1. Load controller PID. There is no pressure control loop of regulating stage in the unit, and only the power closed-loop control loop, namely the load controller PID loop in the model, is available for normal operation with load (see Figure 2). According to the logic setting parameters, the PID parameters of load controller are: \( K_P = 0.1; K_I = 0.1; K_D = 0.0 \).

3.2.2. Primary frequency modulation function deadband. According to the results of primary frequency regulation test, the dead zone of primary frequency regulation function test is \( \pm 1 \text{ r/min} \), and \( \pm 1 \text{ r/min} \) corresponds to the dead zone of speed regulation system control model \( (\text{GJ} / \text{GJ}^+) \pm \varepsilon / 2 \), then the dead zone of model frequency difference is: \( 1 \times 2 / 1500 = 0.0013 \text{ p.u.} \).

3.2.3. Speed deviation magnification. Due to the slow process of nuclear island thermal power regulation, in order to realize the rapidity of primary frequency modulation, the frequency difference feedforward link is set in the control logic of the regulation system, which is realized by the load feedforward control coefficient, according to the set value \( K_2 = 0.6 \). According to the results of primary frequency regulation test, for the speed deviation of \( 1 \text{ r/min} \), the adjusted load is \( 14.48 \text{ MW} \), then the frequency difference magnification \( K \) in the model is calculated.

\[
K = \frac{14.48/1086}{1/1500} = 20.0
\]  

3.2.4. Upper and lower limits of primary frequency regulation load. The parameters of "upper limit of primary frequency regulation load" and "lower limit of primary frequency regulation load" in GJ model should be the frequency difference limit of primary frequency regulation because their actual limit lies in the frequency difference input link. The frequency difference of primary frequency regulation of the unit is limited to \( \pm 4.75 \text{ r/min} \), which is converted to the standard value of \( \pm 4.75/1500 = \pm 0.003167 \), that is, the parameters of "upper limit of primary frequency regulation load" and "lower limit of primary frequency regulation load" in GJ model are \( +0.003167 \) and \( -0.003167 \) respectively.

4. Thermal actuator modeling

After the primary frequency control action of the unit, the command of regulating valve is sent to the servo system to drive the thermal actuator to act to make the regulating valve of the turbine act. According to the structure and characteristics of the field equipment, the servo mechanism of the unit regulating system conforms to the control system structure of BPA electro-hydraulic servo system model (GA/GA+, as shown in Figure 4). According to the logic setting value of the control system, the PID parameters of the electro-hydraulic conversion PID module in the model are: \( K_P = 20.0; K_I = 0.0; K_D = 0.0 \).

Figure 4. Electro hydraulic servo system model.
In order to test the influence of the parameters of the electro-hydraulic conversion PID module on the simulation accuracy of the thermal actuator, 10% step test was carried out. Through 10% step test of No.1 control valve’s thermal actuator of steam turbine, the PID parameters of electro-hydraulic conversion PID module are used for simulation calculation. The actual measurement and simulation curves of 10% closing and opening step test of the thermal actuator are shown in Figure 5.

![Actual measurement and simulation curve of 10% closing and opening step process of No. 1 regulating valve](image)

Figure 5. Actual measurement and simulation curve of 10% closing and opening step process of No. 1 regulating valve (the red line is the measured curve and the blue line is the simulation curve).

It can be seen from Figure 5 that the actual measurement is basically consistent with the simulation curve, which shows that the PID parameters of electro-hydraulic conversion PID module \( (K_p = 20.0; K_i = 0.0; K_d = 0.0) \) in the simulation model can reflect the actual action of the thermal actuator.

Compare the actual and simulation curves of 10% closing step process and 10% opening step process of No. 1 regulating valve respectively. See Table 1 and Table 2 for the comparison data. The data in the table shows that the actual and simulation curve deviation of the two processes are within the allowable range. The above analysis shows that when the simulation PID parameters are the same as the actual unit servo system PID parameters, the simulation can accurately reflect the action characteristics of the actual thermal actuator, which also checks the accuracy of the model PID parameters.

| Table 1. 10% lower step simulation error (s). |
|---------------------------------------------|
| Fall time | Adjustment time |
| simulation | 0.19 | 0.30 |
| Measured deviation | 0.18 | 0.24 |
| Allowable deviation | + 0.2 | + 1 |

| Table 2. 10% step simulation error (s). |
|------------------------------------------|
| rise time | Adjustment time |
| simulation | 0.20 | 0.29 |
| Measured deviation | 0.19 | 0.24 |
| Allowable deviation | + 0.2 | + 1 |

5. Prime mover modeling

5.1. Composition of prime mover
The prime mover is a three cylinder four exhaust, intermediate reheat, reaction condensing and half speed turbine. The flow passage part of the turbine is composed of one double flow high pressure cylinder and two double flow low pressure cylinders, as shown in Figure 6.
5.2. BPA modeling of prime mover
According to the composition of the flow passage part of the prime mover, it is close to the "turbine model (TB)" of BPA, and the block diagram of TB model is shown in Figure 7. In the prime mover modeling, the low-pressure cylinder is taken as the medium pressure cylinder part of TB model, and the low-pressure cylinder part of TB model is removed, that is, the power ratio coefficient of low-pressure cylinder $F_{LP}$ in the model is set to be 0, and the time constant of connecting pipe of low-pressure cylinder $T_{CO}$ in the model is set to be 0.0 s.

5.3. Calculation of power factor of turbine cylinder
The power factor $F_{HP}$ and $F_{IP}$, respectively, represents the percentage of high and low pressure cylinder power in the whole machine power, which meets the following requirements:

$$F_{HP} + F_{IP} = 1 \quad (2)$$

The rated power of HP cylinder is 388.792.5 MW and that of LP cylinder is 697.207.5 MW. See Table 3 for specific parameters. According to the data in Table 3, we can get: $F_{HP} = 388.792.5 / 108.6 = 35.8 \%$, $F_{IP} = 697.207.5 / 108.6 = 64.2 \%$

Table 3. Unit parameters under rated condition.

| Parameter                        | Unit     | Data       |
|----------------------------------|----------|------------|
| Turbine power                    | MW       | 1086       |
| Main steam flow                  | kg·s⁻¹   | 1536.333   |
| Main steam enthalpy value        | kJ·kg⁻¹  | 272.4      |
| One extraction flow rate         | k·s⁻¹    | 128.820    |
| One extraction enthalpy value    | kJ·kg⁻¹  | 2652.7     |
| Two extraction flow rate         | kg·s⁻¹   | 86.973     |
| Second extraction enthalpy value | kJ·kg⁻¹  | 2 598.6    |
| Exhaust flow of HP cylinder      | kg·s⁻¹   | 1 318.055  |
| HP cylinder exhaust enthalpy     | kJ·kg⁻¹  | 2 503.4    |
| Steam leakage of high pressure cylinder shaft seal | kg·s⁻¹ | 1.274   |
| HP cylinder power                | MW       | 388.792.5  |
| Low pressure cylinder power      | MW       | 697.207.5  |
| HP cylinder power factor         | %        | 35.80      |
| Power factor of low pressure cylinder | % | 64.20     |

5.4. Calculation of natural overshoot coefficient of HP cylinder power
Under the condition, the inlet pressure of HP cylinder $P_1 = 6.430$ MPa, and the exhaust pressure of HP cylinder $P_2 = 1.052$ MPa. The natural overshoot coefficient of HP cylinder power can be calculated according to the following formula [11]:

$$\lambda = \frac{\varepsilon^2}{1 - \varepsilon^2} + \frac{k - 1}{k} \cdot \frac{\varepsilon^{\frac{k-1}{k}}}{1 - \varepsilon^{\frac{k-1}{k}}} \quad (3)$$
Substituting \( k = 1.3; \varepsilon = P2/P1 = 0.16361 \) into formula (3), we can get:

\[
\lambda = \frac{\varepsilon^2}{1 - \varepsilon^2} + \frac{1.3 - 1}{1.3} \cdot \frac{\varepsilon^{1.3 - 1}}{1 - \varepsilon^{1.3 - 1}} = 0.4725
\] (4)

5.5. Prime mover model parameter test

5.5.1. \( T_{CH} \) identification results. According to the electromagnetic power data of generator measured by frequency dynamic disturbance test, the average value of volume time constant \( T_{CH} \) of high pressure steam chamber is 0.6s by least square method, and the identification results of negative frequency difference and positive frequency difference are 0.6s. The negative and positive frequency difference simulation and measurement curves are shown in Figure 8 respectively.

![Figure 8](image1)
(a) Negative frequency difference
(b) Positive frequency difference

**Figure 8.** Electromagnetic power simulation (blue) and measured curve (red) of negative and positive frequency difference generator.

5.5.2. \( T_{RH} \) identification results. According to the data of steam inlet pressure of low pressure cylinder measured by frequency dynamic disturbance test, the volume time constant \( T_{RH} \) is identified to be 9.5s by using the least square method. The identification results of negative frequency difference and positive frequency difference are all 9.5s. The negative and positive frequency difference simulation and measurement curves are shown in Figure 9 respectively.

![Figure 9](image2)
(a) Negative frequency difference
(b) Positive frequency difference

**Figure 9.** Simulation (blue) and measured curve (red) of inlet steam pressure of low pressure cylinder with negative and positive frequency difference.

5.5.3. \( T_{CO} \) value. Because the low pressure cylinder inlet of the nuclear power unit is reheated steam without low pressure connecting pipe, the volume time constant \( T_{CO} \) of the low pressure connecting pipe is taken as 0.0.
6. Generator kinetic energy test

The kinetic energy of the generator unit passes the rated load rejection test of the unit. The unit is equipped with rated load (1078 MW during the test), and the breaker at the outlet of development motor is disconnected. The unit is switched from power control to speed control mode, and the speed target value is 1500 r/min. Before the generator outlet breaker is disconnected and the steam turbine regulating valve starts to operate, all the mechanical power of the unit is converted into kinetic energy and stored on the rotor shafting. The process of turbine speed flying up after the rated load rejection of the unit is shown in Figure 10. It can be seen from the rotational kinematics that the kinetic energy change of the unit in t period can be calculated by equation (5).

$$\frac{1}{2} J (\omega^2 - \omega_0^2) = \int_0^t P \, dt$$

(5)

Where: $J$ is the moment of inertia of the turbine generator rotor of the unit, kg·m$^2$; $\omega_0$ is the speed of the generator at the beginning of load rejection, rad/s; $\omega_1$ is the speed of the generator after the rapid rise of $T$ seconds after load rejection, rad/s; $\omega_2$ is the rated speed, rad/s; $P_0$ is the power of the generator before load rejection, W.

According to the load rejection data, there are:

$$3.14159265^2 \times 1500 \times 0.1 = \omega_0 \tag{6}$$

$$25.0653 \times 60 \times 2 \times 3.14159265 \times 0.1 = \omega_1 \tag{7}$$

$$25.2649 \times 60 \times 2 \times 3.14159265 \times 0.1 = \omega_2 \tag{8}$$

Substituting formula (5), we can get:

$$\frac{1}{2} J [(25.2649 \times 60 \times 2 \times 3.14159265)^2 - (25.0653 \times 60 \times 2 \times 3.14159265)^2] = 1078 \times 10^6 \times 0.102 \tag{9}$$

Namely $J = 555 \, 526.8$ kg·m$^2$

Then the inertia time constant of the rotor $T_J$ is:

$$T_J = 2H = \frac{1000 \times (1500 \times 0.1 \times 3.14159265^2)}{1222.2} = 11.215 \tag{8}$$

The kinetic energy of the generator $E_{MWS}$ is:

$$E_{MWS} = \frac{(T_J \times S_{N,gen})}{2} = \frac{11.215 \times 0 \times 0}{2} = 6853.54 \text{ MWs}$$

![Figure 10. Turbine speed rising process after rated load rejection.](image1)

![Figure 11. Comparison between simulation results and actual measurement results (blue for simulation, red for actual measurement).](image2)

7. Model simulation and field test verification

To sum up, the GJ, GJ +, GA, GA + and TB models and their parameters corresponding to BPA program users can be obtained. In order to verify the accuracy of the model and its parameters, field tests were carried out, and the measured results were compared with the simulation results.
The unit has a load of 920.5 MW, and the primary frequency modulation test is carried out under the power closed-loop control mode. The frequency modulation speed reference steps from 1500.00 \text{ r/min} to 1495.35 \text{ r/min} (change + 0.158 Hz). Put the model parameters obtained by the model and field measurement and identification into the power flow and stability calculation database of China Southern Power Grid Corporation, and carry out simulation calculation and Analysis on the test condition in BPA. The comparison between the simulation results and the measured results of the electromagnetic power change process of the generator set is shown in Figure 11.

It can be seen from Figure 11 that the trend of simulation curve is basically consistent with that of actual measurement curve. By analyzing the curve in Figure 11, the simulation and measured data of maximum output increment $P_{HP}$, peak power time $T_{HP}$ and regulation time $T_S$ of $HP$ cylinder can be obtained (see Table 4) [12]. According to the data in Table 4, the deviation of $P_{HP}$. $T_{HP}$ and $T_S$ is within the allowable range. This shows that the simulation results reflect the action characteristics of the primary frequency modulation of the nuclear power unit under the power closed-loop control mode (i.e. governor power closed-loop mode).

Table 4. Comparison of simulation and measurement results.

| Power closed-loop | $P_{HP}$/MW | $T_{HP}$/s | $T_S$/s |
|-------------------|-------------|------------|----------|
| Measured curve    | 32.6        | 3.76       | 11.05    |
| Simulation curve  | 31.5        | 3.77       | 11.35    |
| deviation         | 3.5%        | 0.01       | 0.30     |
| Allowable deviation | + 30%      | + 0.2      | + 2      |

8. Concluding remarks

According to the participation of nuclear power unit prime mover and its governing system in the dynamic process of primary frequency regulation of power grid, the models of governing system, thermal actuator and prime mover are established. This technology is suitable for BPA. The method of model parameter test and identification is designed for the model, and the test of generator kinetic energy is carried out at the same time. The simulation results show that the simulation results are correct, and the model and parameters can accurately reflect the dynamic characteristics of the primary frequency modulation of the nuclear motor group under the power closed-loop control mode.

In the process of modeling, the primary frequency regulation field test of nuclear power unit is carried out, which also shows that nuclear power unit can participate in power grid frequency regulation normally. The proposed primary frequency modulation modeling and simulation technology of nuclear power plant is a new method of nuclear power unit modeling and field model parameter measurement. Through this technology, the accurate simulation of nuclear power participating in the primary frequency regulation characteristics of power grid and the accurate control of frequency modulation load in the simulation process are realized.

References

[1] Tang Zhenpeng, Chen Shihe, Wu Yuzhong, et al 2013 Primary frequency modulation dynamic simulation of PWR nuclear power plant [J] Grid technology 57 (11) 206-210
[2] Jin Na, Liu Wenying, Cao Yinli, et al 2012 Influence of primary frequency regulation parameters of large capacity units on frequency characteristics of power grid [J] Power system protection and control 40(1) 91-100
[3] Li Wang, Jie Zhao, Dichen Liu, et al 2017 Parameter Identification with the Random Perturbation Particle Swarm Optimization Method and Sensitivity Analysis of an Advanced Pressurized Water Reactor Nuclear Power Plant Model for Power Systems [J] Energies 10 173; doi:10.3390/en10020173
[4] Sharma P, Natesan K, Selvaraj P, et al 2014 Dynamic modeling of steam water system of prototype fast breeder reactor using RELAP code [J] Annals of Nuclear Energy 68 209-219
[5] Jun Wang, Jie Zhao, Dichen Liu, et al 2017 Security Constraints and Optimal Operation of Large-scale Nuclear Power Plant Participating in Peak Load Regulation of Power System *IET Generation, Transmission & Distribution* **11**(13) 3332-3340, doi: 10.1049/iet-gtd.2017.0091

[6] Jie Zhao, Tian Liu, Yu Zhao, et al 2016 Reliability evaluation of NPP’s power supply system based on improved GO-FLOW method *Science and Technology of Nuclear Installations* 1-10

[7] Cheng Chen, Zhao Jie, Liu DiChen, Jia Jun, Liang ShanShan, Lin Xue 2014 Power supply safety assessment of a nuclear power plant, based on fuzzy comprehensive evaluation, *International Conference on Energy and Environmental Engineering*, Hong Kong, 2014.9.21-2014.9.22

[8] Jun Wang, Jun Jia, Jie Zhao, Dichen Liu 2014 Study on Power Supply Reliability of Nuclear Power Plant with GO-FLOW Methodology Based on Simulink *2014 International conference on Energy and Environmental Engineering conference*, Hong Kong 2014.9.21-2014.9.22.

[9] J. Zhao, Y.H. Tang, L. Wang and D.C. Liu 2014 The Balance of Power System Peak Load Regulation Considering the Participation of Nuclear Power Plant *Applied Mechanics and Materials* Beijing P.R. China 2014.7.20-7.22.

[10] YeKui Chang, Rao Liu, Chong Wang, et al 2013 Study on the control strategy of the third frequency adjustment with the participation of the nuclear power [C] *Applied Mechanics and Materials* 448-453, 2556-2563

[11] Tian Yunfeng, Guo Jiayang, Liu Yongqi, et al 2007 Mathematical model of reheat condensing steam turbine for power grid stability calculation [J] *Power grid technology* **55**(5) 39-44

[12] DL/T 1235-2013, Parameter testing and modeling guide for synchronous generator prime mover and its regulating system