Thermal unit load optimization control method based on nonlinear dynamic compensation of governing valve

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Abstract. Thermal power generating units are the main force of frequency modulation and peak modulation in Chinese power grid. The accuracy of power regulation of thermal units is directly related to the stability of power grid frequency. Through the analysis of typical grid fluctuations and the characteristics of primary frequency compensation(PFC) and automatic power generation control(AGC) assessment indicators, it is concluded that the linearization of the turbine governing values have a direct impact on the unit’s actual power capacity, which in turn affects the safety and stability of the grid operation. The problem that the valve flow characteristic curve function cannot be automatically adjusted in real time, the dynamic adjustment method to solve the valve non-linearity is proposed to improve the load regulation capacity of the unit.

1. Introduction
There are three important features in the development of modern power system. First, the power grid is extensively interconnected and the region of a single power grid is increasingly wide. Second, new energy sources such as photovoltaics and wind power, large-capacity energy storage equipment are connected to the grid. Third, single generator or the capacity of the line is huge, and long-distance transmission such as UHV is becoming normal[1]. The interaction between the equipment in the power system and the power grid is becoming more and more complex. The power grid will inevitably be interfered by various sudden events or faults when it is running. Once there is a large power shortage, it needs to have certain self-adjusting ability[2], as the main means of grid load adjustment: PFC and AGC, and they are becoming more and more important.

As far as the current situation is concerned, PFC and AGC of Chinese power grid are mainly by conventional thermal units. For the regional power grids such as East China power grid, which have a large external input power through UHV transmission. At present, the frequency modulation capability of UHV transmission itself is still obviously lacking, it puts higher requirements on the thermal power generating unit[3]. So, the frequency modulation task of the thermal power unit in the local power grid is more arduous. For this reason, the major power plants combined with the characteristics of their own units, while using conventional frequency modulation means to further explore the potential of
turbine generator units, but also adopt such means as PFC homologous transformation and condensate water throttling[4,5] to improve the frequency modulation capacity, and remarkable results have been achieved.

However, it can be seen from the performance of large power shortage faults in previous regional power grids that the PFC capability of the thermal units is not stable, and the frequency modulation capability is high or low. When the accident occurred, the grid frequency dropped much more than expected, and the risk of power system operation increased dramatically. At the same time, the adjustment quality of the AGC is unstable, resulting in the time of the grid frequency return to 50Hz is also different. The main reason of the problem is that the non-linearity of the valve characteristics which has a great influence on the dynamic load adjustment of the unit, except for the low main steam pressure and the imperfect PFC logic.

2. Grid's PFC and AGC Standard

With the rapid development of power grid and the continuous expansion of new energy capacity, higher standards and requirements have been put forward for thermal power generating units that are the main force of load regulation in Chinese power grid.

2.1 PFC Standard

The unit’s PFC system automatically control the increase or decrease of the active power according to the grid frequency deviation, to limit the change amplitude of grid frequency, so that the grid frequency maintain the stability of automatic control process. According to the statistics of IEEE, the characteristic time of PFC is about 10 seconds, it is fast response to the changes of grid frequency. The action time of different types thermal unit’s PFC is 0.5 to 2 minutes inequality according to the different heat storage capacity.

As required in the Chinese GB/T 30370 Guide of primary frequency control test and performance acceptance for thermal power generating units standard and GB/T 26863 etc., the dead band of primary frequency compensation(DB) is ±0.033Hz or ±2r/min, the response delay time(DT) is no more than 3 seconds, the stabilization time(ST) is less than 1 minute, the droop is 3%-6%.

The DB is sent to the coordinated control system (CCS) and the digital electric hydraulic(DEH) respectively. On the CCS, the DB passes through the speed governing droop function to generate the corresponding frequency-power setting value, which is superimposed on the unit power setting value to generate the unit power setting value. On the DEH, the DB passes through the speed governing droop function to generate the corresponding comprehensive valve position increment, superimposed to the valve position command signal sent from the CCS, and generates the comprehensive valve position command to control the turbine valve. The increment of comprehensive valve position on the DEH directly affects the opening degree of turbine regulating valve, so the response speed on the DEH is relatively fast, so as to meet the speed requirement of power grid frequency modulation.

2.2 AGC Standard

PFC is an important way of grid frequency control, but, because of its attenuation characteristic and differ regulation, cannot to control the power system frequency depending solely on it. To realize zero error output adjustment of frequency, it must rely on the frequency of the AGC. The adjustment way of AGC for grid frequency is no deviation. Based on the characteristics of the PFC, it is known that due to the time of secondary regulation response is relatively slow, therefore cannot adjust those fast load random fluctuation, but it can effectively adjust the minutes level and longer cycle load fluctuation. When the power grid has a large scale power loss, only PFC is unable to achieve the final stability. Such as AGC action timely, accurate, then the power grid frequency stability will be relatively stable. According to the rules of grid dispatch center, the operation of unit’s AGC must to be run in accordance with the scheduling curve, it put forward three parameters. Figure 1 shows that during the one AGC adjustment, the curve is divided into three sections, corresponding to three assessment index parameters of the power grid.
Adjustment rate $K_1$. According to the requirement of dispatch center, the rate of drum boiler unit is $1.5\% \text{Pe}(\text{unit's rated power})$, thermal power units with intermediate storage pulverizing system is $2\% \text{Pe}$, circulating fluidized bed units and supercritical once-through boiler unit is $1.0\% \text{Pe}$. Adjustment accuracy $K_2$. There are difference between the actual output of unit and the set point of EMS when unit work stably after a response, the permissible deviation is $1\% \text{Pe}$. Response time $K_3$. Response time refers to, after the EMS system send commands, on the basis of the original output point, the time that the output of generating unit reliably adjust to across adjusting dead zone to need. AGC response time of thermal power unit should be less than 1 minute.

Figure 1. Schematic diagram of AGC indicators calculation

3. Non-linearity of unit's load regulation

From the above grid standards, the main concern of grid is the accuracy of unit load regulation capacity, and the performance indicators of PFC and AGC need to meet the standards, but in the actual operation, PFC and AGC performance is unstable.

3.1 Instability of the unit's PFC capability

In the actual operation of thermal power units, the instability of PFC capability often occurs. First, PFC capability is good when the power grid has small frequency difference, but it is bad when the power grid has large frequency difference. Second, when the power grid has the same frequency modulation demand at different times, the actual PFC capability of the same unit has obvious difference. In 2015, the East China power grid repeatedly experienced large power shortages due to UHV DC blocking. Table 1 shows the details of the grid when three faults occurred.

The three faults in Table 1 were the most serious on September 19, and the lowest frequency of East China power grid dropped to 49.563Hz, which was restored to normal 50Hz after about 6min. On July 13 and October 20, the two fault load losses and grid frequency decline is similar. At the time of three faults, the power grid frequency decreases significantly, and the load response of each unit is required to be near the upper limit value of the unit's PFC power (GB30370 is 6\%Pe). Therefore, the performance of each unit's PFC capacity at three faults theoretically should be the same. However, when the fault occurred on September 19, there were few qualified unit’s PFC, and there were many qualified units of the other two faults. The performance of the same unit varied greatly in each fault. For one thing, the data show that the unit's PFC capability is qualified, which can effectively reduce the power grid's frequency decline. For another thing, it also shows that the instability of the PFC capacity of the power grid.

Table 1. Typical fault conditions of UHV DC blocking in East China power grid

| Date  | Grid Load | Power Loss | Unit load rate | Lowest Frequency |
|-------|-----------|------------|----------------|------------------|
| July 13 | 164830    | 3686       | 73\%           | 49.825           |
| Sep.19 | 139260    | 4900       | 65\%           | 49.563           |
| Oct.20 | 121680    | 3710       | 60\%           | 48.792           |
3.2 Unit’s AGC quality fluctuation

In the actual operation, it was found that the indicator value of AGC-R mode is calculated daily. As can be seen from table 2, the AGC-R index value of the unit dropped sharply after a single maintenance. By observing the actual load control curve in the unit’s DCS and the AGC indexes calculated in the power dispatching system, it was found that the load control quality of the unit fluctuate greatly, and the local index variation leads to a significant decrease in the overall index.

Table 2. Unit’s AGC-R index value

| Date  | Unit | K1   | K2   | K3   |
|-------|------|------|------|------|
| 6-18  | LQ#1 | 1.164| 1.168| 1.821|
| 6-19  | LQ#1 | 1.067| 1.091| 1.795|
| 6-20  | LQ#1 | 1.174| 1.166| 1.825|
| 9-12  | LQ#1 | 0.396| 0.390| 1.623|
| 9-13  | LQ#1 | 0.717| 0.746| 1.688|
| 9-14  | LQ#1 | 1.096| 1.152| 1.775|

For the power grid, because the focus of attention is on the rapid response capability of the unit, according to the above analysis, it can be concluded that the control quality problem of the turbine side of the unit needs to be studied.

Figure 2. Unit’s CCS of power plant

4. Reason analysis

The thermal unit load controller essentially maintains the balance between thermal power in the boiler, and mechanical-electrical power in the turbine generator. The fundamental to the balance is the main steam pressure at the turbine governor valves. The coordinated control system is used as shown in Figure 2.

When the unit operate in CCS mode, the boiler mainly control the main steam pressure, and the turbine side mainly control the power output. The unit sets the power target value locally or remotely from the grid dispatch centre. According to most plants now controlled by distributed control systems, it is fairly straightforward to set controller parameter values for stable operation over an acceptable load range. How to effectively ensure coal-air-water appropriate action when the PFC or AGC act, is the key to reduce the unit fluctuations and ensure the safe operation of the unit. As shown in Figure 2, it can be seen that whether it is AGC or PFC, the common output is the steam turbine. The steam turbine adjusts the load of the unit by controlling the opening of the governing valve. The adjustment characteristics of the governing valve and the initial position have a significant influence on the AGC and PFC capability. The control of the steam turbine is realized by distributing the comprehensive opening command of the governing valve to each governing valve through the distribution function.
The relationship between the comprehensive opening command and the steam flow through all the governing valves is called steam turbine flow characteristics. In theory, the flow characteristics of the steam turbine should be linear. The PFC capability of the unit will remain stable. However, due to the installation, equipment aging, etc., the flow characteristics of many units are non-linear, and the degree of linearity is also different.

The flow characteristics of steam turbine determine the unit’s load regulation capacity. The fundamental reason for the unstable load regulation capacity of the unit is that the local speed unequal rate difference is too large under the opening of the steam turbine. Figure 3 is the load control performance fluctuations of unit LQ#1 flow characteristics. The analysis of the flow characteristic curve shows that the flow characteristics of the steam turbine are linearly inferior, and the following is taken as an example for further explanation.

The unit LQ#1 is equipped with 4 governing valves, and the #1/#2 governing valve maintains synchronous action. It is basically in the fully open position when the load is more than 50%, and the performance is obviously deteriorated before and after the overlapping area of the unit governing valve, such as #1/#2 overlaps area A of #3, overlap area B of #3 and #4. Especially at point A, the flow characteristics are nonlinear, and the actual load tracking load command of the unit is slow. The amplitude of PFC and AGC performance index cannot meet the grid requirements.

5. Optimization and promotion

Since the function of the unit’s governing valve is preset, as shown in Figure 4, the specific value of each valve f(x) is calculated according to the flow rate, that is, the opening value of each governing valve. It is generally possible to perform special flow characteristic tests after the unit is overhauled, and automatic real-time adjustment cannot be achieved during normal operation. Therefore, the project innovatively proposed a dynamic adjustment control method for the parameters of thermal unit. According to the historical operation data of the unit, the actual flow rate and target flow rate under different flow command F(x) are obtained, which are non-linearly identified and then linearized regression, through the dynamic evaluation of parameters to ensure linearization of load regulation.

![Figure 4. Linearization analysis of the unit’s flow characteristic curve](image-url)
The project focuses on the estimation method of the non-linear characteristics of the governing valve of the steam turbine based on daily operation data, which can automatically estimate the non-linear characteristic curve of the governing valve of the steam turbine from the historical operation data of the thermal unit. The project studied the cooperative method of nonlinear compensation and control parameter adjustment, realized the inverse function operation of the nonlinear characteristic curve by adjusting the proportion and integral parameters of the power controller, and compensated the negative influence of the nonlinear characteristics of the high tuning door of the steam turbine on the load control performance of the unit.

6. Conclusion
Aiming at the flow non-linearity of the steam turbine governing valve and its actual situation that seriously affect the performance of the unit’s PFC and AGC, the nonlinear estimation and compensation technology of the governing valve of the steam turbine can be developed. The governing valve can be estimated from the historical operating data, and quantitatively evaluate the influence of nonlinear characteristics on control performance. The technical means of coordinating the nonlinear compensation and controller parameter adjustment can be obtained, avoiding or reducing the nonlinear characteristics of the governing value to the actual power control performance. The technology can overcome the shortcomings of the existing periodic manual testing methods, and make the estimation, evaluation and compensation of the nonlinear characteristics of the steam turbine governing valve in an automated and systematic manner to ensure the economic and safety of the generator set operation. The safe and stable operation of the power grid and the unit is realized.

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