Research on access rules and flexibility evaluation index system of ancillary service market in China

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Abstract. In high renewable energy penetrated power systems, the flexibility of power system resources is indispensable. With the implementation of domestic ancillary service markets, the revenue of ancillary services provided by generating units is gradually changing from the planned mode to the market mode. Moreover, the access threshold for generating units to participate in the ancillary service market has changed. At the same time, the flexibility of generating units has a great impact on the revenue of the ancillary service market. Therefore, this paper summarizes the flexibility requirements of typical pilot areas in China for generating units to participate in ancillary service markets. Then, the corresponding flexibility evaluation indexes of different ancillary services are sorted out and the flexibility evaluation model is developed to evaluate the flexibility ability of power generation enterprises scientifically. The flexibility evaluation system proposed in this paper can effectively evaluate the flexibility capability of generating units and conduct its flexibility enhancement.

1. Introduction

Power ancillary service refers to the service provided by power generation enterprises, power grid operation enterprises and power users in addition to normal power production, transmission and consumption, to maintain the safe and stable operation of the power system and ensure the power quality [1-3]. In the context of carbon peaking and carbon neutrality target, the proportion of renewable energy penetrated in the power system will increase dramatically in the future. The flexibility of generator units has been considered by all countries to be the key to achieving a high proportion of renewable energy power systems [4-5]. Therefore, to deal with the variability and uncertainty of renewable energy, the demand for ancillary services will be increased accordingly. Moreover, with the release of "No. 9 Government Document", the reform of China's power market is steadily advancing [6]. As an important component of the power market, the ancillary service market has attracted widespread attention [7]. By the end of 2019, 19 regions in China have established the power ancillary service market, and the market-oriented varieties mainly focus on compensable deep peak regulation and frequency regulation services [8]. There are differences in the access conditions and market mechanism design of the generator units in each pilot area [9-10]. To better clarify the status of the ancillary service market and guide the participation of generating units in the ancillary...
service market, it is necessary to summarize the current rules and conditions of the ancillary service market.

Flexibility is the main factor that affects the revenue of generating units in the ancillary service market. On the one hand, units with higher flexibility are in the dominant position in the market-clearing process and can be dispatched first. On the other hand, the unit with better flexibility has higher comprehensive performance. Their compensation revenue for providing ancillary services is higher. Traditionally, the ancillary services provided by the unit are mainly compensated according to the "two rules" [8]. In the ancillary service market, whether the unit can provide ancillary services is affected by their quotation, the performance index, and market clearing result. For instance, the flexibility indexes such as response time, adjustment rate and adjustment accuracy mainly affect the benefit of regulation ancillary service. Peak adjustment depth mainly affects the revenue of peak adjustment ancillary services. Therefore, the flexibility of the unit has a great influence on the market of generating units participating in ancillary services.

Based on the above analysis, this paper investigates the market rules of domestic ancillary services and develops the evaluation system of the flexibility of the generating unit.

2. Ancillary service pilots in China
Generating units should meet the requirements of market rules when participating in the ancillary service market. The electricity regulatory authority organizes the electric power dispatching agency and electric power enterprises to formulate specific assessment methods. The electric power dispatching agency shall evaluate the service provided by units that participate in the ancillary service market. Therefore, this section sorts out the evaluation method for the qualification access of units to participate in the ancillary service market.

2.1. AGC ancillary service

2.1.1. Shandong ancillary service market. The electric power dispatching agency is responsible for determining the qualification of AGC units according to the regulation performance test results of units. At present, the AGC regulation performance is measured by the regulation rate index, the regulation accuracy index, the response time index and the comprehensive AGC performance index. The electric power dispatching agency has the right to cancel the qualification of the AGC device whose performance fails to meet the requirements.

2.1.2. Fujian ancillary service market. The main providers of AGC service in Fujian province are hydropower units with a single unit capacity of 50MW and an adjustable capacity of 20MW or above, thermal power units with a single unit capacity of 300MW and an adjustable capacity of 150MW or above, and gas units with a single unit capacity of 300MW and an adjustable capacity of 100MW or above.

To encourage energy storage equipment to provide AGC ancillary service, the capacity of energy storage equipment and electric power stations shall be no less than 10MW temporarily, and they shall participate in the AGC market according to the standard of conventional units. The AGC market sets the access threshold which requires the comprehensive performance index $K$ not less than 0.2, and adjusts the threshold according to the actual operation of the market.

2.1.3. Shanxi ancillary service market. Thermal power units with AGC devices and new energy units that meet corresponding technical standards, energy storage equipment operators, retailers, and users can participate in the AGC market.
The electric power dispatching agency shall calculate the historical average AGC performance index of each AGC provider afterward, and shall not call it when the index is lower than the limit value. AGC providers can enter the AGC market again after they meet the standard.

2.1.4. Guangdong ancillary service market. Generation units that participate in the Guangdong AGC market should meet the following conditions: (1) Install AGC devices according to relevant regulations of grid-connection management. (2) AGC performance index is counted according to the generation unit. The electric power dispatching agency publishes the comprehensive AGC performance index of the generation unit daily, and calculates the comprehensive AGC performance index in the last 8 winning hours. The entry threshold of the Guangdong AGC market is that the comprehensive AGC performance index is not less than 0.5, which shall be adjusted according to the operation of the AGC market. (3) Market entities equipped with factory-level AGC should choose one of the two modes of factory-level AGC and stand-alone AGC to participate in the Guangdong AGC market at the time of quotation, and must ensure that the mode selected when quoting is consistent with the actual input mode.

2.1.5. Zhejiang ancillary service market. Generation units that participate in the Zhejiang AGC market should meet the following conditions: (1) AGC device shall be installed according to the relevant regulations of grid-connection management. (2) Meet the relevant requirements of the Rules for Grid-connected Operation Management of Power Plants in East China. (3) AGC performance index is counted according to the generation unit. Zhejiang electric power dispatching agency releases the comprehensive AGC performance index of generation units daily, and calculates the comprehensive AGC performance index with the most recent 12 winning periods. The entry threshold of the AGC market shall be no less than 0.5 for the comprehensive AGC performance index, which shall be adjusted according to the operation of the AGC market. The performance index of AGC ancillary service includes the regulation rate index, response time index and regulation accuracy index, as well as the comprehensive performance index.

2.2. Peak regulation ancillary service

2.2.1. Shandong ancillary service market. The output of units or the power flow of connection lines shall be less than the paid peak regulation criterion. The starting criterion for the paid peak regulation of units shall be 70% of the declared maximum output power, and the starting criterion for the paid peak regulation of the cross-provincial connection line shall be 70% of the peak power.

2.2.2. Fujian ancillary service market. At the beginning of the transaction, the units providing deep peak regulation service are coal-fired thermal power and nuclear power units, LNG units and pumped storage units with two-part electricity price will not participate in the deep peak regulation market. Units involved in deep peak regulation transactions need to actively reduce their output power to a load rate less than the paid peak regulation benchmark, which is 60% for coal-fired thermal power units and 75% for nuclear power units.

The range of power plants that participate in the unit start-stop peak trading is the power plants directly regulated by the province and licensed for dispatching, with a single unit capacity of no less than 50 MW. The power storage facilities involved in peak trading should be charged at a scale of not less than 10 MW/40 MW.

2.2.3. Shanxi ancillary service market. Coal-fired units whose average load rate is lower than the benchmark can participate in the deep peak regulation market.
2.3. Reserve ancillary service
In Zhejiang ancillary service market, generation units that provide reserve ancillary service should meet the relevant requirements of the Rules for Grid-connected Operation Management of Power Plants in East China.

2.4. Summary and comparison
Next, this paper summarizes the trading products, providers and performance requirements of the most advanced power markets in Fujian, Zhejiang, Shandong and Guangdong, as shown in Table 1.

By summarizing the power ancillary service market in various regions, we can see that in terms of trading varieties, the domestic market-oriented varieties mainly include regulation ancillary service and peak shaving service. Thermal power units can provide the most kinds of ancillary services. In addition, all domestic pilot ancillary service markets have put forward performance requirements for the performance of ancillary services provided by units.

| Table 1. Comparisons of four provincial ancillary service market. |
|---------------------------------------------------------------|
| **Trading products**                                      | **Provider**                                      | **Performance requirements**                        |
|---------------------------------------------------------------|
| Deep Peak Regulation                                         | Thermal power units and nuclear power units       | The paid peak shaving benchmark of coal-fired thermal power units is 60%, and that of nuclear power units is 75%. |
| Start-up and Shut-down Peak Operation                        | Hydropower units and coal-fired power units       | unit capacity ≥ 50000 kW                           |
| Peak regulation of electric energy storage                   | Generation side, user side and independent electric energy storage | The charging capacity shall not be less than 10MW / 40 MWh |
| Regulation                                                   | Hydropower units                                  | unit capacity ≥ 50000 kW                           |
|                                                             | Thermal power units                                | Adjustable capacity ≥ 20000 kW                      |
|                                                             | Gas unit                                           | unit capacity ≥ 300000 kW                          |
|                                                             | Energy storage equipment                           | Adjustable capacity ≥ 100000 kW                     |
|                                                             |                                                    | The frequency regulation market sets the admittance threshold for the unit performance, and requires the comprehensive index k of the unit frequency regulation performance not less than 0.2 |
| Guangdong Province                                           | Grid-connected power generation units and third-party auxiliary service providers regulated by provincial and above power dispatching agencies | It is located in the unified frequency control area of the southern power grid, and has an AGC function. The entry threshold of the FM market is not less than 0.5 for the comprehensive FM performance index, and the comprehensive FM performance index is calculated in the last 8 winning hours. |
| Zhejiang Province                                            | Meet the relevant requirements of the implementation rules for grid-connected operation and management of power plants in East China; The entry threshold of the regulation market is that the comprehensive FM performance index is not less than 0.5, and the comprehensive FM performance index is calculated based on the latest 12 bid winning periods. |
| Shandong Province                                            | The grid-connected power plant under provincial dispatching command is equipped with an AGC device. | The power dispatching organization is responsible for determining the qualification of AGC units according to the results of the unit regulation performance test |
| Deep Peak Regulation                                         | Nuclear power, thermal power units and trans provincial connecting lines to Shandong | unit capacity ≥ 100000 kW                          |
3. Flexibility index and the flexibility evaluation model

3.1. AGC performance index

The three most important indexes to characterize the comprehensive regulation performance of AGC units are response time, regulation rate and regulation accuracy. Among them, the measurement processes of response time, regulation rate and regulation accuracy are independent of each other. Firstly, the time of response instruction is captured, then the regulation rate is measured after the unit begins to execute the instruction. Finally, the regulation accuracy is calculated after the target value is reached and maintained for a period of time.

3.1.1. Response time. According to the "two rules", if the response time is more than the standard response time of the unit, the penalty will be imposed. When the response time is less than the standard response time of the unit, compensation will be given. Therefore, the response time index of the i-th regulation \( K_{ri} \) is constructed:

\[
K_{ri} = 2 - \frac{T_{ei} - T_{si}}{T_N}
\]

where \( T_{si} \) is the starting time of the i-th regulation; \( T_{ei} \) is the time corresponding to the first time the unit crosses out of the regulation dead zone consistent with the regulation direction, \( T_N \) is the rated capacity of the unit. The response time of thermal power units should be less than 1min, and the response time of hydropower units should be less than 10s.

3.1.2. Regulation rate. According to the "two rules", when the regulation rate is lower than the standard regulation rate of the unit, it will be penalized; otherwise, it will be compensated. Therefore, the regulation rate index of the i-th regulation \( K_{ri} \) is as follows:

\[
K_{ri} = \begin{cases} 
\frac{P_{ei} - P_{si}}{(T_{ei} - T_{si})v_N} & P_j \notin (P_{ei}, P_{si}) \\
\frac{P_{ei} - P_{si}}{|(T_{ei} - T_{si})|v_N} & P_{ai,j} \in (P_{ei}, P_{si})
\end{cases}
\]

where \( P_{ei} \) and \( P_{si} \) are the output power at the end and start of regulation respectively; \( T_{ei} \) and \( T_{si} \) are the end time and the beginning time of regulation respectively; \( P_j \) is the critical point power of unit start-stop grinding; \( T_j \) is the time consumed by starting and stopping the mill; \( v_N \) is the standard regulation rate of the unit.

3.1.3. Regulation accuracy. According to the "two rules", when the regulation deviation is higher than 1% of the rated capacity of the unit, it will be punished; when it is lower than 1% of the rated capacity of the unit, it will be compensated. Therefore, the regulation accuracy index of the i-th regulation is constructed:

\[
K_{ri} = 2 - \frac{\int_{\Delta t_{ji}}^{} |P(t) - P_j|}{0.01P_N}
\]

where \( T_{si} \) is the first time to enter the regulation dead zone; \( T_{si} \) is the new AGC instruction setpoint command time; \( P_j \) is the set point instruction value within the period; \( P_N \) is the rated capacity of the unit.

3.1.4. Comprehensive performance index. At present, most of the AGC performance evaluation methods used in China use the weighted balance method. In the actual system application, the weighted aggregation method has disadvantages of the small difference in AGC performance indicators of each unit, better indicators mask poor indicators and weight setting difficulties. Therefore, the multiplication formula is used to calculate the comprehensive performance index of the AGC
service. This comprehensive performance index takes into account the impact of response time, regulation rate and regulation accuracy. When one indicator is better (greater than 1) and the other indicator is worse (less than 1), the multiplication of the two indicators will reduce the final value, thus more reasonably characterizing the regulation performance of AGC units. The AGC comprehensive regulation performance index is calculated as follows:

\[ K_{pi} = K_1 K_2 K_3 \] (4)

Specially, the evaluation standard of AGC comprehensive regulation performance index is presented in Table 2.

### Table 2. Evaluation standard of AGC comprehensive regulation performance index.

| Evaluation value | 0-1 | 1-2.5 | 2.5-3.5 | 3.5-5.0 | > 5.0 |
|------------------|-----|-------|---------|---------|-------|
| Evaluation condition | Very poor | Poor | General | Good | Excellent |
| Scores | 0-60 | 60-70 | 70-80 | 80-90 | 90-100 |

#### 3.2. Peak regulation performance index

The peak regulation capacity of the unit is related to the regulation characteristics of the unit, fuel type, start/stop cost, unit capacity and other factors. Generally speaking, the larger the adjustment range of unit output and the larger the capacity of the unit, the greater its peak regulation capacity.

##### 3.2.1. Regulation depth

To measure the peak regulation capacity of the unit more conveniently, the peak regulation depth index of the unit is usually defined according to the maximum and minimum technical output of the unit:

\[ K_{pi} = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}}} \] (5)

where \( P_{\text{max}} \) and \( P_{\text{min}} \) are the maximum and minimum technical output of unit \( i \) respectively. \( K_{pi} \) reflects the regulation ability of the unit. Different types of generation units have different maximum output and different regulation performance. In general, if the unit \( K_{pi} \geq 0.7 \), it is considered that the unit has a strong peak regulation ability. The peak regulation depth of hydropower units and some thermal power units with no-load operation is close to or up to 1.0, while the value of pumped storage units can even reach 2.0.

##### 3.2.2. Start-up and shutdown time

There is no absolute comparability between start-up and shutdown time for thermal power units with different installed capacities. For example, the start-up and shutdown of large thermal units take dozens of hours, while the start-up and shutdown of small thermal units only take a few hours. Therefore, after standardized treatment of start-up and shutdown time, its evaluation indexes are defined as follows:

\[ K_{si} = \frac{UDT}{P_{\text{max}}} \] (6)

where \( UDT \) is the minimum start-up and shutdown time of the unit. The shorter the start-up and shutdown time of the unit, the stronger the peak regulation ability.

##### 3.2.3. Maximum regulation rate

The maximum regulation rate evaluation index is defined as similar to the start-up and shutdown time, as follows:

\[ K_{ri} = \frac{RU}{P_{\text{max}}} \] (7)

where \( RU \) is the maximum regulation rate of the unit. The larger the maximum regulation rate of the unit, the stronger the peak regulation ability.
3.2.4. Comprehensive performance index. Ancillary service performance indexes can be divided into benefit-oriented and cost-oriented. According to their specific meanings, benefit-oriented indexes are those whose value is greater and better, and cost-based indexes are smaller and better. $K_b$ and $K_c$ are benefit-oriented indexes, $K_{ci}$ belongs to cost-oriented indexes, combined with the "two rules" and domestic and foreign research results, the comprehensive performance index of peak regulation is defined as:

$$K_p = \frac{K_b K_c}{K_{ci}} \quad (8)$$

3.3. AVC performance index

According to the quantitative assessment of reactive power compensation and AVC in the "two rules", based on existing research results at home and abroad and in the principle of rationality, science and practicality, the following provisions are made for the evaluation indexes for AVC ancillary service.

3.3.1. Phase modulation range. Phase modulation range indicators are as follows:

$$K_b = \frac{\Delta Q}{\Delta Q_0} \quad (9)$$

where $\Delta Q$ is the difference between the measured maximum reactive power output and the minimum reactive power output of the unit; $\Delta Q_0$ is the reference value of the difference between the maximum reactive power output and the minimum reactive power output of the capacity unit.

3.3.2. Average reactive power regulation rate. The average reactive power regulation rate index of the phase-in operation of the unit is defined as:

$$K_{2i} = \frac{V_i}{V_N} \quad (10)$$

where $V_i$ is the reactive power regulation rate of the unit; $K_{2i}$ is the average reactive power regulation rate of the unit, when it is greater than 1, it is treated as 1; $V_N$ is the standard reactive power adjustment rate of the unit.

3.3.3. AVC operation rate. The calculation formula of AVC operation rate index is as follows:

$$K_y = \frac{t_c}{t_a} \quad (11)$$

where $t_c$ is the monthly operation time of AVC; $t_a$ is the monthly operation time of the unit. the benchmark of the AVC operation rate is 98%, when the monthly operation rate is more than 98%, the index score is 1. When the AVC device of the grid generation unit operates in a closed-loop with the AVC of the corresponding electric power dispatching agency main station, and the monthly operation rate of AVC is less than 98%, the score of this indicator is $K_y / 98\%$.

3.3.4. Qualified rate. Through the EMS system, the qualified rate of AVC reactive power regulation shall be automatically counted and assessed monthly. The qualified point shall be the point of tracking the main station's reactive power instruction to reach the specified dead zone within 5 minutes for each regulation, otherwise, it shall be the unqualified point. The formula for calculating the qualified rate of AVC reactive power regulation is as follows:

$$K_{4i} = \frac{Y}{Y_0} \quad (12)$$

where $Y$ is the number of qualified points for AVC regulation; $Y_0$ is the number of orders issued by the dispatching agency. The qualified rate of AVC reactive power regulation is calculated according to a single unit, and the benchmark of the qualified rate is 100%.
3.3.5. **Comprehensive performance index.** Because $K_{1i}$, $K_{2i}$, $K_{3i}$ and $K_{4i}$ are benefit-oriented indexes, the comprehensive performance index of reactive power regulation is defined as follows:

$$K_{pi} = K_{1i}K_{2i}K_{3i}K_{4i}$$  \hspace{1cm} (13)

3.4. **Reserve performance index**

3.4.1. **Maximum reserve capacity.** The maximum reserve capacity index refers to the ratio of the maximum reserve capacity provided by the unit to its maximum technical output.

3.4.2. **Ramp rate.** The ramp rate index is the load lifting speed of the unit. The higher the ramp rate, the shorter the time it takes for the unit to rise from the original output point to the new output point issued by the dispatching agency.

3.4.3. **Comprehensive performance index.** Because $K_{1i}$ and $K_{2i}$ are benefit-oriented indexes, the comprehensive performance index for the reserve is defined as follows:

$$K_{pi} = K_{1i}K_{2i}$$  \hspace{1cm} (14)

3.5. **Black start performance index**

Reasonable selection of evaluation indexes is a key link in the comprehensive evaluation of black start units. The overall goal of system recovery after a blackout is to restore the system with load capacity in the shortest recovery time, and a good black start-up scheme should have the characteristics of rapid recovery, safe and reliable, and strong load capacity. Therefore, the evaluation of black start should be carried out from time, reliability and restored power generation, which can be summarized as follows:

1. **Factors related to recovery time,** as shown in Table 3, mainly include the start-up time of the self-start unit, the status and start-up characteristics of the start-up unit, the ramp rate and the number of equipment operations. Among them, although the status and start-up characteristics of the start-up unit are the key factors for the selection of the start-up unit, they are directly related to the period from the start of the black starting power supply to the restart of the started power plant and the actual situation on the scene, so it is difficult to determine in advance.

2. **The main factors related to the reliability of system recovery,** as shown in Table 3, include the phase-in capability, line length, number of voltage conversions, the number of operations of the device and the quality of the verification indexes. Each calibration index should be kept as far away from its critical state as possible, so in the evaluation of the black start scheme, the maximum operation voltage multiply, automatic excitation of the generation, the maximum deviation degree of the system frequency variation, and the maximum deviation degree of the bus voltage change of the started power plant are used to evaluate the advantages and disadvantages of the calibration index.

| Benefit-oriented indexes | Cost-oriented indexes |
|--------------------------|----------------------|
| The number of device operations on the path $w_i$ | The capacity that was started $M_1$ |
| The length of the path line $w_i$ | The in-phase ability $M_2$ |
| The number of path voltage conversions $w_i$ | The load importance $M_3$ |
| The overvoltage multiply $w_i$ | The ramp rate $M_4$ |
| The deviation of the factory bus voltage $w_i$ | The automatic excitation $M_5$ |
| The degree of deviation of the system frequency $w_i$ | Start-up time $w_i$ |

**Table 3. Black start evaluation index classification.**
3.6. The flexibility evaluation model

After the evaluation indexes of different kinds of ancillary service are determined, the Multi-level flexibility evaluation system as shown in Figure 1 is constructed in this section to evaluate the overall flexibility of units.

In the comprehensive evaluation of the flexibility of generation units, the indexes must be standardized. The common methods include the reciprocal inverse transformation method and the reverse inverse transformation method. For the comprehensive evaluation of multi-level indexes, a very simple evaluation idea is to quantify each evaluation index according to a certain method, and then obtain the total evaluation value based on the quantitative value of the index and the weighted synthesis according to a certain synthesis model. Common comprehensive evaluation methods include artificial neural network (ANN), data envelopment analysis (DEA), gray relational analysis (GRA) and technique for order preference similarity to ideal solution (TOPSIS).

![Figure 1. The multi-level flexibility evaluation system.](image)

4. Conclusions

Under the goal of carbon peak and carbon neutralization, the total amount of renewable energy consumption in the power grid will gradually increase. Due to the large fluctuation of renewable energy, the demand for flexible resources such as peak shaving and the climbing rate is further increased. This paper analyzes the requirements for flexibility of generator units in the domestic ancillary service market, then summarizes the key flexibility indicators corresponding to different types of ancillary services, and finally puts forward a multi-level flexibility evaluation system for power generation enterprises to participate in the ancillary service market. Through the proposed evaluation system, the flexibility of the generator set can be evaluated, which can provide direction for the flexibility transformation of the generator units and enhance the competitiveness of the generator set in the ancillary service market.

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