AGC unit capacity planning model considering auxiliary service market under the background of China’s new electricity reform

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Abstract. With the advancement of a new round of power system reform and the continuous access to renewable energy, the auxiliary service market has received extensive attention as an important service to ensure the safe and reliable operation of the power grid. However, it is difficult for the automatic generation control (AGC) units in the system to meet real-time fastness requirements of the power market. Based on the premise that “market electricity” and “planned electricity” coexist under the background of new electricity reform, this paper focuses on the upgrade and reconstruction of AGC units in “planned electricity”. With capacity matching and speed matching as the planning objectives, the optimization and reconstruction algorithm and model of the AGC units are established. Taking capacity matching and speed matching as research targets, the optimization and reconstruction algorithm and model of the AGC units are established. Finally, the effectiveness of the model and the specific scheme of the AGC unit optimization and reconstruction are established through simulation.

1. Introduction
With the release of the Electric Power Circular 9, various regions of China will gradually open up the electricity market in the future [1]. The scale of transactions in the electricity market is gradually expanding. The planned electricity share will continue to shrink, so the frequency modulation capacity of AGC units will also be smaller. In addition, with the rapid development of new energy sources and the impact of carbon emissions on power generation constraints, the growth rate of thermal power plant construction continues to slow. At the same time, the volatility of new energy power generation is strong, and the demand for rapid regulation of the power grid has increased significantly [2-4]. Therefore, optimizing the capacity of the AGC units and ensuring that the AGC units can better adapt to the auxiliary market is the key to solving the problem.

Establishing a reasonable auxiliary service market plays an important role in ensuring the safety and reliability of electrical energy. In literature [5], distributed power sources, energy storage systems and demand response resources in the microgrid were aggregated to participate in the auxiliary service market. In literature [6], authors took offshore wind power as the research object and proposed an AGC scheduling method that considers the random prediction error of offshore wind power generation. In reference [7], a method was proposed for adaptively determining the sag coefficient of the generator set for the operating stability margin of the hybrid AC/DC network. Javier García-González has
proposed that pumped storage units cooperate with wind turbines to participate in the power spot market in [8]. The above literatures mainly considered the market mechanism design of the auxiliary market, but few literatures have studied the impact of the new auxiliary service market on power planning.

Regarding the impact of China’s new round of power reform on frequency modulation, domestic researchers have studied and tried. In literature [9], He Y et al studied the design of cost allocation mechanism of frequency modulation service; In reference [10], Ma H et al considered the optimal operation model of the regional integrated energy system participating in the FM market; In reference [11], Liu Y analysed the frequency regulation market of Shanxi Electric Power in China, and its frequency regulation service aimed at the lowest total cost of supply. In reference [12], Chen H et al designed an AGC scheduling system framework and market mechanism with energy storage participation.

At present, China’s frequency modulation task is still the responsibility of the AGC unit. In order to adapt to the power frequency modulation market, the optimization and capacity expansion of AGC units will receive more attention. This article aims at the optimized operation of AGC units participating in the auxiliary service market. The paper first analyzes the operating mechanism in the auxiliary service market, including the AGC execution mechanism and transaction model under the market; then analyzes the impact of the FM market on planning from the perspective of FM capacity and FM speed; Finally, A specific FM capacity configuration scheme is obtained through simulation examples.

2. Auxiliary service market

2.1. FM service and ACE assessment under the auxiliary service market

The frequency modulation (FM) service under the electricity market means that the AGC unit provides sufficient adjustable capacity and a certain adjustment rate to the market within 5 minutes. Through the monitoring of the power of the tie line, the frequency can be tracked in real time under the allowable area control error (ACE) to meet the requirements of system frequency stability.

The determination of FM capacity is mainly based on ACE. The dispatch center aims to ensure the stability of ACE in a certain area. When the frequency difference exceeds a given amount, each frequency-modulated power plant is adjusted by the power grid until the frequency returns to the set value. The province-adjusted AGC adjustment plan is:

\[ E_{ACE} = \Delta P + K_i \Delta f \]  
\[ \Delta P = P_j - P_{sj} \]  

Where, \( \Delta P \) is the deviation power of the tie line; \( P_j \) is the actual power exchanged by the tie line; \( P_{sj} \) is the planned power of the tie line; \( K_i \) is the deviation coefficient of the provincial grid frequency; \( \Delta f = f - f_0 \) is the difference between the actual frequency of the system and the reference frequency.

The operation of ACE must meet the following two conditions:

1. The value of ACE should go through zero within 10min, which is shown in the Figure 1. The formula is

\[ E_{ACE} = 0, \forall t \in [0, 10\text{min}] \]  

2. ACE cannot exceed the upper and lower limits. which is:

\[ |E_{ACE}| \leq \eta \]  

The assessment constraints are shown in Figure 1.
2.2. Operating mechanism of auxiliary service market
As shown in Figure 2, in the auxiliary service market, the market clearing of AGC consists of the following steps:

Step 1: According to the deviation value of ACE, the power grid dispatch center issues the AGC frequency modulation demand.
Step 2: During the quotation period, power plants with AGC units make quotations on the spot FM market;
Step 3: During the game period, combine the capacity of each power plant and the frequency modulation rate to conduct a bidding game to obtain the right to frequency modulation;
Step 4: During the implementation period, the power plant that meets the AGC frequency regulation needs to start the automatic control equipment to participate in the secondary frequency regulation.

2.3. Division method of load curve
When implementing frequency control, the provincial grid dispatcher controls the output of the AGC unit to meet the balance of power generation and consumption across the entire network. According to the adjustment capability of the generator, the power generation part can be divided into several components: tie-line planned component, non-AGC component, tracking the previous day component, tracking the intra-day rolling planned unit component and the AGC adjustment component, as shown in Figure 3.

Among them, the tie-line plan component refers to the transmission of electricity from one area to another. Non-AGC units generally refer to some units that are not equipped with automatic generation controllers, so they cannot participate in auxiliary services and also serve as base load components. Tracking intra-day rolling plan and tracking previous day plan units are also composed of local units. The AGC adjustment component refers to maintaining the frequency stability of the local power grid according to the ACE assessment, and using the AGC frequency modulation unit in the region to complete the task.
3. Optimization algorithm of AGC unit in auxiliary service market

3.1. AGC unit capacity planning objective function
The optimization of AGC units in this paper includes the construction of new units and the upgrading of old units to ensure the matching of FM capacity and FM rate. The objectives of the plan include the investment cost of the new unit and the upgrade cost of the old unit. The expression is as follows:

\[
\min C = \min \sum_{y} \sum_{\text{new \ AGC}} \left( X_{\text{new,AGC}} c_{\text{new}}^l + X_{\text{exist,AGC}} c_{\text{upgrade}}^l \right)
\]

Where: \(C\) is the total investment costs of the AGC units in total planned year; \(n_y\) is the total planned year; \(\Omega_{\text{new \ AGC}}\) is the set of AGC unit to be planned; \(X_{\text{new,AGC}}\) is the capacity of the newly-built AGC unit; \(c_{\text{new}}^l\) is the unit investment cost of the newly-built AGC unit; \(X_{\text{exist,AGC}}\) is the capacity of the existing AGC unit to be upgraded; \(c_{\text{upgrade}}^l\) is the unit investment cost of the AGC unit to be upgraded.

3.2. Constraints of optimization model
Constraint equation of power balance in the region is:

\[
P_{\text{load}} = P_{\text{line}} + P_{\text{non,AGC}} + P_{\text{G,plan}} + P_{\text{AGC}}
\]

Where, \(P_{\text{load}}\) is the total demand capacity caused by the load change; \(P_{\text{line}}\) is the planned adjustment component of the tie-line; \(P_{\text{non,AGC}}\) is the power generation capacity of the non-AGC unit; \(P_{\text{G,plan}}\) is the adjustment component of tracking the planned unit; \(P_{\text{AGC}}\) is the AGC unit frequency modulation demand.

Constraint of annual load power supply margin in the region

\[
G + H_{\text{new}}^{\text{max}} \sum_{\text{new \ AGC}} X_{\text{new,AGC}} > D
\]

Where, \(G\) is the historical power generation amount of the existing power supply; \(H_{\text{new}}^{\text{max}}\) is the annual maximum utilization hour of the newly added AGC unit; \(D\) is the predicted electricity consumption in the area.
The output constraints of the mth generator is:

\[ P_{Gm,\text{min}}^t \leq P_{Gm}^t \leq P_{Gm,\text{max}}^t \] (8)

Among them, \( P_{Gm,\text{min}}^t \) and \( P_{Gm,\text{max}}^t \) are the minimum output and maximum output of the mth generator respectively.

Constraint equation of AGC unit climbing rate is:

\[
\begin{align*}
V_i^t &\geq \max \left( \frac{\Delta P_{j,t+\Delta t} - \Delta P_{j,t}}{\Delta t} \right), \quad j = 1, 2, \ldots, 12 \\
V_{d}^i &\geq \max V_i^t, i \in [0, 24] \\
V_{\text{year}}^i &\geq \max V_{d}^i, k \in [0, 365]
\end{align*}
\] (9)

Where, \( V_i^t \) is the maximum frequency adjustment rate demand in the i-th hour segment; \( \Delta P_{j,t+\Delta t} \) is the deviation value at the j-th node at time \( t + \Delta t \); \( V_i^t \) is the deviation value at the j-th node at time \( t \); \( V_{d}^i \) is the maximum speed demand on the k-th day of the year; \( V_{\text{year}}^i \) is the maximum speed demand for the year.

3.3. AGC unit optimization model considering auxiliary service market

The model of the AGC unit optimization algorithm considering the background of the new electricity reform is shown in Figure 4, and the algorithm steps are as follows:

Step 1: Regarding the capacity matching problem, information on power operating conditions such as the load power in the region, the amount of electricity delivered from other provinces, and the installed capacity of the local power supply needs to be obtained.

Step 2: According to the number of AGC units in the area and the capacity of each AGC unit in the local unit data, the maximum frequency modulation amount available in the area is obtained.

Step 3: According to Figure 3, the load curve is decomposed into four power generation components. According to formula (8-14), the frequency modulation demand of the region is calculated, and the future frequency modulation growth of the region is obtained according to the prediction algorithm.

Step 4: Based on the maximum FM capacity and FM demand in the area, the capacity of the AGC unit optimization and transformation in the future can be obtained.

Step 5: Considering the frequency adjustment time constraint of the auxiliary service market, the frequency adjustment rate demand result in the region is calculated.

Step 6: We compare the conventional scheme with the optimized transformation scheme proposed in this article. The conventional scheme retains the original old unit, adds a new unit, and selects some
units to participate in AGC frequency modulation; the optimization and transformation scheme first reduces some old units that do not meet the frequency response speed conditions, and adds new units with loads that meet the frequency adjustment conditions.

Step 7: According to the comparison of the cost of the plan, the optimal planning result is selected.

4. Example analysis

4.1. Local power operation data

This paper takes the typical load area as the research object, and this area needs to receive power from other provinces through the tie line, which conforms to the calculation model of this paper. Due to the serious problem of peak and frequency modulation, it is of great practical significance to use it as a research object.

Table 1 shows the operation of the region from 2014 to 2017. The operating parameters of a typical AGC units are shown in Table 2. FM units account for the installed capacity in this region as shown in Figure 5.

Table 1. Electricity Operation in a Region in 2014-2017.

| Year | Power generation / 100 million kWh | Generator capacity /10,000kW | Maximum load of electricity /10,000kW |
|------|----------------------------------|-----------------------------|--------------------------------------|
| 2014 | 808.14                           | 2183.68                     | 2680.20                              |
| 2015 | 821.19                           | 2343.68                     | 2981.90                              |
| 2016 | 832.32                           | 2370.65                     | 3138.40                              |
| 2017 | 865.50                           | 2399.67                     | 3268.20                              |

Figure 5. 2017 installed capacity in the region.

It can be seen from Table 1 that the power generation in this area is less than the power consumption in this area, and some of the electrical energy is transmitted to the area through the contact line from other provinces. Two indicators, the maximum load of electricity consumption and the annual consumption of electricity, indicate the growth of electricity demand in the region.

Figure 5 (a) shows the total and proportion of AGC units and non-AGC units in the installed capacity of the region. AGC units account for approximately 40% of the total installed capacity. Figure 5 (b) distinguishes whether the electricity generated by AGC units participates in the main energy trading market or the FM auxiliary service market. It can be seen from Figure 5 that the power generated by the AGC unit has a capacity of about 67.4 MW to participate in the main energy transaction, and the remaining 28.6 MW capacity can be used to participate in FM auxiliary service transactions.

4.2. FM capacity matching result

Since the peak daily load is the moment when the frequency modulation is the largest in a day, the power generated by the local unit is about 40% of the total. Local units are divided into real-time AGC
units and tracking plan units. The tracking plan unit participates in the main energy transaction in the power market, while the real-time AGC unit participates in the auxiliary service market. The power planning capacity of the AGC unit required can be obtained from the peak load.

According to the proportion of AGC units participating in auxiliary service is 29.8%, the FM demand for each year obtained by decomposition of the load curve is shown in Figure 6.

**Figure 6.** Load of the highest load day of 2014-2017.

From the maximum demand for FM in Figure 6 compared with the FM capacity for the AGC units in Figure 5, it is found that the current FM capacity is sufficient. In order to meet the future FM demand, and reserve a 100,000 kW margin as the FM supply. Therefore, the installed capacity of the AGC unit and the total installed capacity can be planned as shown in Table 2.

| Year | FM demand /10 000kW | AGC unit capacity /10 000kW | Generator capacity /10 000kW |
|------|----------------------|-----------------------------|-----------------------------|
| 2021 | 276.8                | 956                         | 2400                        |
| 2022 | 288.8                | 996                         | 2490                        |
| 2023 | 300.8                | 1036                        | 2590                        |
| 2024 | 312                  | 1073                        | 2682.5                      |

4.3. FM rate matching result
In order to meet the requirements of the AGC frequency regulation rate, the real-time statistics of the grid load calculate the annual load maximum frequency regulation rate requirement according to formula (12-14). And on this basis, We forecast the future demand for FM rate. It can be calculated that the FM rate demand in 2024 is 113 MW•min⁻¹.

4.4. Planning results
First, the difference between the current power operating parameters and the predicted value is used as a reference for the optimization or reconstruction of the AGC unit; then, the effects of the traditional planning scheme and the optimization and transformation scheme proposed in this paper are considered separately; finally, a comparison is made to select the optimal scheme. The comparison results of the two schemes are shown in Table 3.

| Type                      | Conventional plan | Optimize transformation plan |
|---------------------------|-------------------|-----------------------------|
| Total number              | 21                | 17                          |
| Total installed capacity /MW | 11600            | 10800                       |
| FM capacity /MW           | 3460              | 3230                        |
| Speed regulation /MW•min⁻¹ | 113               | 114                         |
It can be seen from Table 3 that the optimized transformation scheme proposed in this paper has significant advantages over the conventional scheme in terms of the number of devices and the frequency modulation rate, and can better meet the requirements of the frequency modulation auxiliary market for increasing the frequency modulation rate. At the same time, the elimination of backward units with slower speed regulation also reflects that the auxiliary service market has improved the competitiveness of thermal power units.

5. Conclusions

Aiming at the optimization and transformation of AGC units under the background of new electricity reform, this paper draws the following conclusions with a certain area as the research object:

1. With the advancement of new electricity reforms, the requirements for speed regulation of AGC units will become higher and higher, and small-capacity units with poor speed regulation capabilities will face the situation of being eliminated.

2. Although the investment and construction of thermal power units will slow down in the future, by replacing low-efficiency thermal power units with faster speed and larger capacity thermal power units, it can better adapt to the future power market.

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