Study on Frequency Regulation of Energy Storage for Hydropower Station

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Abstract: The paper firstly proposes energy storage frequency regulation for hydropower stations. Taking the actual operating hydropower station as an example, it analyzes the necessity of configuring energy storage to participate in frequency regulation for hydropower stations, and according to the hydropower station AGC regulate situation, the battery capacity of the energy storage frequency regulation system is designed, and the frequency regulation performance of the energy storage frequency regulation system at different battery capacities is analyzed. It provides reference for hydropower stations with similar needs.

1. Introduction
At present, favorable market policies for frequency regulation auxiliary services and the rapid development of energy storage technology are driving the vigorous development of energy storage frequency regulation projects in thermal power plants[1-3]. On the one hand, the energy storage joint frequency regulation has effectively increased the AGC adjustment speed of the unit, and further met the needs of grid dispatching[4-5]. On the other hand, the high AGC compensation fee under the policy support has brought considerable benefits to the power plant, and the capital payback period is short. Various energy storage system integrators have turned in to investors, hoping to use policy as an opportunity and capital as leverage to win AGC compensation benefits. Since 2017, major energy storage suppliers and thermal power plants have carried out a series of energy storage frequency regulation projects, using the rapid adjustment performance of the energy storage system to cooperate with the thermal power unit to perform AGC frequency regulation to obtain compensation. At home and abroad, there is currently no idea of energy storage frequency regulation for hydropower stations.

2. Necessity of frequency regulation for hydropower station energy storage
The actual case of a hydropower plant is used to illustrate the necessity of energy storage frequency modulation.

A hydropower plant in Hunan Province has a total installed capacity of 150MW. It uses 3 ZZ-LH-595 axial-flow rotary-propeller units with a single-unit capacity of 50MW, with an outlet voltage of 220kV, it is a provincial-level straight-pipe power plant. The AGC frequency regulation of Hunan Power Grid is mainly undertaken by 7 hydropower plants. When the active power deviation of the tie line is large and the standby regulating capacity of the hydropower plant is insufficient, the...
thermal power plant will then participate in the AGC regulation. As an important force for AGC frequency regulation in Hunan Province, the hydropower plant has frequent regulation, large frequency regulation mileage, and high regulate speed, resulting in frequent power generation equipment failures and shortening the overhaul period from 10 years to 5 years, which has a huge impact on the safe and stable operation of the power plant.

A hydropower plant B in Guangxi has a single unit capacity of 700MW, with a total installed capacity of 4900MW, the AGC response accuracy is not up to standard. At present, in the new auxiliary service market, the power grid has increased requirements for AGC adjustment accuracy. For large units, the adjustment step length of the AGC system is much larger than the regulation accuracy. If the regulation step length in the AGC system is shortened, the unit will frequently shake and cause vibration. Exceeding the standard has an impact on the stability of the unit, and after the step length is shortened, the adjustable range within the same time will be reduced, resulting in the frequency regulation mileage not meeting the corresponding requirements, and also bringing AGC compensation benefits.

In the above two cases, referring to the successful experience of thermal power plants in solving frequency regulation problems, it is proposed to learn from the method of energy storage and frequency regulation, and add a set of large-scale energy storage systems with fast response speed and high sensitivity to assist the power generation and operation of hydropower plants. At the same time as the equipment safety problems brought by the AGC adjustment of the hydro power plant units, it also obtains the benefits of the auxiliary service market.

3. 2 AGC regulation performance and analysis of a hydropower plant in Hunan

Hydropower plant A has certain particularities in terms of primary frequency regulation and AGC frequency regulation: 1) The power plant is at the end of the Hunan power grid. Primary frequency regulation is frequently adjusted to track system frequency changes, and there are many AGC commands issued by dispatch and frequent unit adjustments. 2) The hydropower plant is an axial-flow rotary-propeller unit. In the case of a small frequency modulation action, it is very easy to have insufficient integral power. When the AGC action conflicts with the direction of the primary frequency modulation action, the blade opening adjustment lags behind the guide vane opening adjustment in the initial stage of load adjustment of the unit, and the guide blade and the blade are in a non-associated working condition for a short time, especially in the initial stage of load adjustment. It will show a slight increase or decrease, and this characteristic cannot be eliminated from the unit itself. The data of the hydropower plant in July and August are shown in the table below.
### Table 1 AGC performance data statistics table of a hydropower plant in Hunan

| date       | instructions number | adjustment speed(MW/min) | K1  | K2  | K       | daily mileage | average AGC instruction depth | response mileage (15s) | successful bid rate | difference | maximum difference | minimum difference |
|------------|---------------------|--------------------------|-----|-----|---------|--------------|-----------------------------|----------------------|---------------------|------------|-------------------|-------------------|
| 2020/7/1   | 57                  | 52.94                    | 1.06| 0.52| 0.55    | 852.87       | 18.32                      | 13.23                | 84%                 | 5.09       | 15.68             | 1.63              |
| 2020/7/2   | 89                  | 55.84                    | 1.12| 0.52| 0.58    | 1415.39      | 19.21                      | 13.96                | 92%                 | 5.25       | 9.80              | 1.63              |
| 2020/7/3   | 135                 | 55.33                    | 1.11| 0.54| 0.60    | 2103.13      | 18.97                      | 13.83                | 92%                 | 5.14       | 18.43             | 0.47              |
| 2020/7/4   | 235                 | 53.02                    | 1.06| 0.52| 0.55    | 3580.47      | 18.77                      | 13.25                | 87%                 | 5.51       | 18.93             | 1.04              |
| 2020/7/5   | 413                 | 54.69                    | 1.09| 0.54| 0.59    | 6497.56      | 18.99                      | 13.67                | 91%                 | 5.32       | 13.94             | -3.46             |
| 2020/7/6   | 493                 | 52.55                    | 1.05| 0.49| 0.52    | 7524.50      | 18.89                      | 13.14                | 89%                 | 5.76       | 18.46             | 1.21              |
| 2020/7/7   | 971                 | 54.13                    | 1.08| 0.50| 0.54    | 15051.86     | 19.00                      | 13.53                | 92%                 | 5.47       | 16.79             | 0.84              |
| 2020/7/8   | 615                 | 55.97                    | 1.12| 0.52| 0.58    | 9804.63      | 19.32                      | 13.99                | 95%                 | 5.33       | 19.21             | 0.43              |
| 2020/7/9   | 195                 | 54.41                    | 1.09| 0.47| 0.51    | 3046.81      | 19.28                      | 13.60                | 93%                 | 5.68       | 17.60             | 1.20              |
| 2020/7/10  | 307                 | 57.15                    | 1.14| 0.50| 0.57    | 4949.61      | 19.63                      | 14.29                | 97%                 | 5.34       | 19.45             | 1.82              |
| 2020/8/1   | 1041                | 55.08                    | 1.10| 0.51| 0.56    | 16378.78     | 19.26                      | 13.77                | 92%                 | 5.49       | 19.70             | -2.75             |
| 2020/8/2   | 1014                | 55.90                    | 1.12| 0.52| 0.58    | 15948.10     | 19.11                      | 13.97                | 93%                 | 5.14       | 19.98             | -0.66             |
| 2020/8/3   | 879                 | 56.15                    | 1.12| 0.52| 0.58    | 13991.44     | 19.31                      | 14.04                | 94%                 | 5.27       | 19.99             | 0.71              |
| 2020/8/4   | 1067                | 55.37                    | 1.11| 0.52| 0.57    | 16773.69     | 19.08                      | 13.84                | 94%                 | 5.24       | 19.35             | 0.40              |
| 2020/8/5   | 1430                | 52.68                    | 1.05| 0.53| 0.56    | 22171.65     | 18.88                      | 13.17                | 87%                 | 5.71       | 17.90             | -1.88             |
| 2020/8/6   | 1513                | 55.70                    | 1.11| 0.55| 0.61    | 23855.46     | 19.05                      | 13.93                | 91%                 | 5.13       | 19.65             | -0.07             |
| 2020/8/7   | 1515                | 54.21                    | 1.08| 0.54| 0.59    | 23493.24     | 18.79                      | 13.55                | 89%                 | 5.23       | 17.36             | 0.23              |
| 2020/8/9   | 1714                | 56.64                    | 1.13| 0.56| 0.63    | 26750.86     | 18.83                      | 14.16                | 95%                 | 4.67       | 18.74             | -1.72             |
| 2020/8/10  | 333                 | 49.37                    | 0.99| 0.55| 0.54    | 4789.63      | 17.71                      | 12.34                | 76%                 | 5.37       | 13.20             | -0.02             |
| average    | 737.68              | 54.59                    | 1.09| 0.52| 0.57    | 11525.25     | 18.97                      | 13.65                | 91%                 | 5.32       | 17.59             | 0.05              |

(Number of instructions: Provincial adjustment of the number of instructions issued by AGC each day. Average daily adjustment speed: Calculate the adjustment speed of each AGC adjustment process of the day, and take the average of all adjustment speeds of the day. K: Comprehensive FM performance index, which is composed of K1 and K2.)


**K1: Command response speed performance index,**

\[ k_1 = \frac{\Delta P \times T \times (P_f - P)}{abs(\Delta P) \times \Delta T \times abs(P_f - P)} \]

**K2: Command response accuracy performance index,**

Successful bid rate: The AGC frequency modulation command that the unit responds meets the requirements of provincial commissioning and assessment, and the corresponding compensation is obtained as winning the bid, otherwise it is not winning the bid.

Take the data in Table 1 for analysis. Within the statistical scope, AGC adjustment has the following characteristics:

1) AGC regulation is frequent, and there are many regulation times in a single day. Counting the number of AGC adjustments in the 20 days in July and August, the maximum number of AGC regulation was more than 1700, with an average of 772 times, and more than 1000 times in 8 days. Each adjustment process is generally 15 seconds, 20 seconds or 25 seconds, ranging from 1 to 3 times within 1 minute, and the AGC action is very frequent.

2) AGC frequency regulation mileage is large. Single FM mileage is mostly distributed between 12MW and 20MW. For instructions above 15MW, the coverage rate for 10 days is higher than 70%, the coverage rate for 8 days is between 62% and 70%, and the coverage rate is 2 days. The rate is 48%–60%. The maximum daily FM mileage is 26750MW, and the average daily mileage is 12048MW.

3) AGC regulation speed is fast. The maximum single regulation speed of AGC is 1.83PN/min (PN is the capacity of a single unit), generally 0.8~1.5PN/min, and the daily average AGC regulation speed is generally around 1.1PN/min.

According to the above statistics, if the provincial regulation AGC command regulation statistical time is 15 seconds, if the AGC set regulation is 15MW, the regulation rate required for the hydropower plant is 60MW/min, and the single unit capacity PN is 50MW, then the required regulation speed is 1.25PN/min. In order to meet the speed control commands issued by the AGC, the governor guide vanes, blade bushings and other mechanical hydraulic mechanisms frequently operate, and the frequent changes in the force of the runners and other components will cause mechanical wear to the unit, resulting in fatigue of the structural parts, and then affect the life and safe and stable operation of the unit.

**4. Hydroelectric energy storage and frequency regulation battery**

Selection of battery capacity. Mainly consider the size of the AGC instruction and the direction of two adjacent instructions. When the AGC command is less than the battery capacity, the unit does not need to participate in the adjustment, otherwise the unit needs to participate in the adjustment. When the battery can cover all AGC commands, the impact on the unit is minimal. Considering that if two adjacent commands are in the same direction (both increase generator output), the required battery capacity is the superposition of the two commands. At this time, the capacity of the battery will be Surge. From the battery cost combined with the size and direction of the command, three cases of battery capacity of 10MW, 15MW, and 20MW are proposed, and the continuous command rate in the same direction and the command rate that can be covered under different battery capacities are analyzed. The 10MW energy storage system can adjust the power between -10MW (charging) and 10MW (discharging), the adjustable range is 20MW, and the rest of the capacity can be deduced by analogy.
| Date       | Total number of instructions | Proportion | Continuous same direction instruction |
|------------|-----------------------------|------------|---------------------------------------|
|            |                             | <10MW | <15MW | <20MW |                                 |
| 2020/7/1   | 57                          | 3.51% | 22.81% | 47.37% | 45.61%                           |
| 2020/7/2   | 89                          | 2.25% | 20.22% | 66.29% | 50.56%                           |
| 2020/7/3   | 135                         | 5.93% | 26.67% | 77.78% | 42.22%                           |
| 2020/7/4   | 235                         | 5.11% | 34.89% | 87.23% | 47.23%                           |
| 2020/7/5   | 413                         | 2.91% | 27.36% | 92.01% | 42.86%                           |
| 2020/7/6   | 493                         | 5.48% | 32.25% | 93.91% | 48.07%                           |
| 2020/7/7   | 971                         | 4.63% | 30.07% | 96.91% | 46.86%                           |
| 2020/7/8   | 615                         | 2.11% | 23.41% | 95.12% | 47.97%                           |
| 2020/7/9   | 195                         | 0.00% | 20.00% | 84.10% | 41.54%                           |
| 2020/7/10  | 307                         | 0.65% | 20.20% | 90.23% | 49.51%                           |
| 2020/8/1   | 1041                        | 3.65% | 27.76% | 96.73% | 42.36%                           |
| 2020/8/2   | 1014                        | 3.45% | 28.99% | 96.84% | 40.93%                           |
| 2020/8/3   | 879                         | 2.62% | 24.23% | 96.59% | 42.21%                           |
| 2020/8/4   | 1067                        | 3.19% | 26.80% | 96.91% | 40.67%                           |
| 2020/8/5   | 1430                        | 4.41% | 33.22% | 97.27% | 35.10%                           |
| 2020/8/6   | 1513                        | 3.30% | 29.41% | 97.22% | 38.47%                           |
| 2020/8/7   | 1515                        | 7.13% | 31.82% | 97.76% | 40.26%                           |
| 2020/8/9   | 1714                        | 3.15% | 32.85% | 97.78% | 40.49%                           |
| 2020/8/10  | 333                         | 12.31%| 31.53% | 59.76% | 27.93%                           |

July and August average 737.68 3.99% 27.61% 87.78% 42.68%

| Date       | Total number of instructions | Proportion | Continuous same direction instruction |
|------------|-----------------------------|------------|---------------------------------------|
|            |                             | <10MW | <15MW | <20MW |                                 |
| 2020/11/1  | 513                         | 10.33% | 45.61% | 93.76% | 41.13%                           |
| 2020/11/2  | 421                         | 8.79% | 44.42% | 90.74% | 33.25%                           |
| 2020/11/3  | 573                         | 15.88% | 59.51% | 93.72% | 30.02%                           |
| 2020/11/10 | 175                         | 16.00% | 66.29% | 82.29% | 24.00%                           |
| 2020/11/18 | 372                         | 23.39% | 68.28% | 91.94% | 24.19%                           |
| 2020/11/19 | 507                         | 19.53% | 66.27% | 93.29% | 22.68%                           |
| 2020/11/20 | 702                         | 12.96% | 48.58% | 95.73% | 37.46%                           |
| 2020/11/21 | 472                         | 14.41% | 54.24% | 92.80% | 28.81%                           |

November average 466.875 15.16% 56.65% 91.78% 30.19%

Battery discharge rate. At present, energy storage systems can be roughly divided into peak regulation and frequency regulation according to their functions. The discharge rate of energy storage batteries under different functions (representing the speed of discharge, 1C for 1 hour discharge, and 2C for 0.5 hour discharge) has different requirements. Energy storage system, mainly for energy storage, generally requires energy-type batteries, such as 1C, 0.5C batteries; for frequency-egulated energy storage systems, it is mainly for rapid power adjustment, and power types with high discharge rates, such as 2C or even Higher cells.

Estimated battery life. Peak-shaving energy storage batteries generally use deep charge and
discharge, 1-2 times a day, and frequency-regulated energy storage batteries use shallow charge and shallow discharge, and the number of daily charge and discharge increases sharply. In thermal power plants, the number of daily regulation for AGC is generally 300-400, and the battery life Generally 2-3 years. If the number of AGC adjustments per day in the hydropower plant is about 1000, if the battery with a 2C charge and discharge rate is used, the life of the battery is estimated to be 1 year, if the battery with a 1C charge and discharge rate is used, the life of the battery is estimated approximately 2 years.

5. Increase the frequency regulation performance analysis of the energy storage system

Take the November instruction as an example to estimate the instruction coverage and the increase in K value after the energy storage system is added.

5.1. Frequency regulation command coverage

Continuous same direction commands account for 30% (the reverse command is 70%), the average depth of the AGC command is 17MW, the unit can respond to 11.5MW in 15 seconds on average, the average power difference is 5.5MW, and the average regulation rate of the unit in 15s is 0.77MW/s. (1) If a 10MW energy storage system is adopted, the instructions less than 10MW account for only about 15%. Excluding the same direction instructions, the fully covered instructions are about 10% of the total. In most cases, the unit and the energy storage system need to be combined. Regulating active power, the command depth is averaged to 17MW, the response power of the unit in 15 seconds can be reduced to 7MW, the average adjustment rate of the unit in 15s can be reduced to 0.47MW/s, and the average regulation rate can be reduced by 39%. The above is a simplified model. The current command is the reverse of the previous command. If the current command is in the same direction as the previous command, the unit needs to adjust the full power of this command. (2) If a 15MW energy storage system is used, instructions less than 15MW account for 56.7%. Excluding the same direction instructions, the fully covered instructions are about 40% of the total. The remaining instructions still require the unit and the energy storage system to respond together. The same applies Simplified model, the response power of the unit in 15 seconds can be reduced to 2MW, the average adjustment rate of the unit in 15s is reduced to 0.13MW/s, and the average adjustment speed of the unit can be reduced by about 83%. (3) When adding a 20MW energy storage system, the energy storage system alone can respond to 91.8% of the commands, and the reverse command accounts for 70%, and the 20MW energy storage system alone can respond to 64% of the AGC commands alone, which is greater than 20MW. Less, in this case the unit only needs to regulate 1-2MW.

Table 3 Command coverage rate and unit AGC regulation after adding energy storage system

| Command complete coverage | 0MW | 10MW | 15MW | 20MW |
|---------------------------|-----|------|------|------|
| Command complete coverage | 0   | 10.58% | 39.55% | 64.07% |
| Unit average regulated power | 17MW | 7MW | 2MW | 0 |
| Unit average adjustment speed | 1.13MW/s | 0.47MW/s | 0.13MW/s | 0 |

(Command complete coverage: Only the energy storage system can fully respond to AGC commands, without the need for the unit to participate in adjustment.

Unit average regulated power: The amount of power that the unit needs to increase/decrease when responding to AGC commands.

Unit average adjustment speed: When the unit participates in AGC frequency modulation, the amount of power that needs to be adjusted per unit time, the command time is calculated as 15 seconds.)
5.2. Comprehensive K value improvement of unit frequency regulation

At present, the regulation rate index \( K_1 \) of the hydropower plant is 1.2~1.3, and the regulation accuracy index \( K_2 \) is 0.33~0.5. From this, the comprehensive performance \( K \) value can be calculated to be between 0.396 and 0.65. The root cause is the deviation of the unit AGC accuracy performance index. Low. According to the new specification, the requirements for the accuracy index of the generating unit are higher, and the requirement is less than 1% \( P_N \); the regulation deviation of the hydropower plant is required to be less than 1.5MW.

After the construction of the energy storage system, due to the rapid power adjustment of the energy storage system and the accuracy of the power output of the energy storage system, the regulation rate and accuracy of the unit will be greatly improved. From the power plant receiving the AGC command from the grid to the response of the energy storage system to the output power, the maximum response time is 5s. The output power deviation of the energy storage system is 3% of the rated power of the energy storage, which is much smaller than the regulation deviation requirement, and the regulation performance index \( K_2 \) is close to 1. According to the relevant content in the "Two Rules": regulation with an regulation time of less than 10 seconds are considered random fluctuations and are not included in the regulation process statistics, assessment and compensation. At the same time, the system records the power time for 5 seconds. Therefore, the combined output of the energy storage and the unit should reach the AGC command target value at least 15 seconds before it is considered effective. Assuming that after adding a 10MW energy storage system, all commands can be fully responded within 15 seconds. After correcting each evaluation command on this basis, the performance parameter comparison can be obtained as shown in the following table, and the average daily income increased to the original 3 times. If the 15MW energy storage system is added, the average daily income will increase by 4 times. If the 20MW energy storage system is added, the average daily income will increase by 5 times.

Table 4 Comparison table of frequency regulation performance parameters of hydropower plants after adding 10MW/5MWh energy storage system

| Date       | K | K1 | K2  | K | daily mileage | daily benefits | K1 | K2  | daily mileage | daily benefits |
|------------|---|----|-----|---|---------------|----------------|----|-----|---------------|----------------|
| 2020/11/1  | 1.05 | 0.55 | 0.58 | 7491.59 | 28393.12 | 1.43 | 0.95 | 1.36 | 9196.12 | 81166.29 |
| 2020/11/2  | 1.05 | 0.56 | 0.59 | 6164.16 | 23912.49 | 1.44 | 0.95 | 1.36 | 7552.35 | 66915.07 |
| 2020/11/3  | 0.90 | 0.55 | 0.49 | 7867.20 | 25500.76 | 1.37 | 0.95 | 1.30 | 9828.47 | 83409.52 |
| 2020/11/5  | 0.83 | 0.56 | 0.46 | 1650.66 | 4903.04 | 1.35 | 0.95 | 1.28 | 2035.08 | 16957.18 |
| 2020/11/10 | 0.81 | 0.64 | 0.52 | 2216.81 | 7318.73 | 1.24 | 0.95 | 1.18 | 2723.34 | 21148.53 |
| 2020/11/18 | 0.80 | 0.57 | 0.46 | 4706.16 | 14007.79 | 1.28 | 0.95 | 1.21 | 5942.35 | 47175.04 |
| 2020/11/19 | 0.81 | 0.57 | 0.46 | 6613.92 | 19880.00 | 1.30 | 0.95 | 1.23 | 8225.83 | 66444.08 |
| 2020/11/20 | 1.02 | 0.56 | 0.57 | 10054.3 | 38226.20 | 1.41 | 0.95 | 1.34 | 12377.8 | 107706.88 |
| 2020/11/21 | 0.93 | 0.55 | 0.51 | 6523.97 | 21576.29 | 1.37 | 0.95 | 1.30 | 8092.05 | 68814.11 |
| November   | 0.91 | 0.57 | 0.52 | 5920.97 | 20413.16 | 1.35 | 0.95 | 1.29 | 7330.39 | 62192.97 |
6. Conclusion
1) The paper firstly puts forward the concept of energy storage and frequency regulation in hydropower stations, and demonstrates its necessity: hydropower stations with frequent AGC adjustments are likely to cause equipment wear and thus affect the safe and stable operation of the power stations. Hydropower stations with large single-unit capacity lead to power assessment due to insufficient adjustment accuracy.

2) Analyzing the AGC command of a hydropower station in Hunan Province, its AGC adjustment has the following characteristics: frequent adjustment, large frequency regulation mileage, and fast adjustment speed.

3) An energy storage frequency regulation system for the hydropower station is designed, including batteries, primary systems, control systems, etc., and the 10MW/5MWh, 15MW/7.5MWh, 20MW/10MWh energy storage frequency regulation system is analyzed, it will reduce the average adjustment speed of the unit by 39%, 83%, 100%.

4) If the 10MW energy storage system is added, the average daily revenue of the auxiliary service market will increase by 3 times. If the 15MW energy storage system is added, the average daily revenue of the ancillary service market will increase by 4 times. If the 20MW energy storage system is added, the average daily revenue of the auxiliary service market will increase by 5 times.

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