Analysis on operation reliability of hydropower units in China

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Abstract. With the rapid development of hydropower in China, in just a few years installed capacity has leapt to the world's first, in addition to thermal power outside the development of the second largest electricity supply. However, the equivalent availability level of hydropower units in China is lower than that of conventional fossil energy thermal power units, and the cost of unit engineering is higher, especially the unplanned shutdown coefficient of pumped storage units in China is much higher than the world level. Therefore, it is urgent to carry out the research on the operation reliability of generator sets. Based on the analysis and summary of the basic situation, operation situation, planned outage and unplanned shutdown of hydropower units in China, this paper puts forward the main problems of reliability of hydropower units and hydroelectric power plants, which are used for reference and exchange by professional and technical personnel engaged in hydropower industry.

1. Introduction
In the new energy and renewable resources [1], hydropower is a power system with high operating reliability, large adjustable capacity, long service life, relatively low cost and operating costs, technology mature energy storage mode, its operation mode is flexible, rapid response, in the power system has peak-regulating filling, FM phase modulation, A variety of functions, such as emergency standby and black start-up, play a very important role in the safety, stability and economic operation of the power grid [2]. In today [3], when the haze is becoming more and more serious and the people are becoming more and more afraid of the environment caused by the burning of conventional energy, it is an inevitable choice for our country to improve the environment to develop new and renewable energy sources such as hydropower. In recent years, the state under the influence of a series of incentive policies [4], hydropower units installed on a rapid scale, as of the end of 2017, China's grid-connected hydropower units installed capacity of 343.59 Million-kilowatt, an increase of 3.5% year earlier, of which, pumped storage power generation total installed capacity of 28.69 Million-kilowatt, year-on 7.5% [5] growth, the single-machine capacity from the earliest 240-kilowatt to the world's single capacity of up to 1000 megawatts. With the rapid development of the installed scale of hydropower units and the increasing single-machine capacity of hydropower units, the study of the economy of hydropower equipment and the stability of power grid operation has become the focus of domestic attention.

2. Basic situation of hydropower units
Since the beginning of the 20th century, the 2×240 kW hydropower unit of the Yunnan Shilongba Hydropower station has been put into operation. Since then, the prelude to the development of
hydropower in China has been opened, creating a history of transforming clean and renewable water into electricity in China. A batch of 700 MW hydropower units of the Three Gorges, Longtan, Xiaowan and Laxiwa hydropower stations were put into operation, and a batch of 800 MW class-class world-class hydropower units [6] in Xiangjiaba and Xiluodu were put into operation successively, and then the world's largest single machine. The Baishatan Hydropower Station of Jinsha River with a capacity of 1000 MW marks that China's hydropower units have moved from "Made in China" to "Created in China" [7]. According to the characteristics of hydropower resources and the construction demand of hydropower projects in China, hydropower units are divided into five main types.

2.1. Mixed-flow hydroelectric unit
The mixed-flow turbine, also known as the Frances Turbine, flows along the radial direction into the wheel and then rotates roughly along the axial rotation. Mixed-flow turbine is one of the most widely used hydraulic turbines in modern times because the application of water head is suitable for the needs of most areas, as well as simple structure, reliable operation and high efficiency. To the 1980s, China's largest mixed-flow hydroelectric unit for the Dragon and Sheep Gorge hydropower station 320 MW. With the development of water conservancy and hydropower in China, especially the construction of Three Gorges hydropower station and the development of hydropower in the west, the application and manufacture of hydropower units in China have unprecedented development. By the end of 2017, our country has been put into operation of 700 MW hydropower units are mixed-flow hydropower unit, about 76 units. It is expected that by 2020, China's operational 700 MW and above hydropower units will reach about 100 units [6]. Among these units, more than 50% units are designed and manufactured independently by China's hydropower manufacturing enterprises. Mixed-flow hydroelectric unit is the most rapid development in China and the most outstanding results of the model.

2.2. Axial flow hydropower unit
The flow of water in the runner region of the axial flow turbine flows axially, and the flow of water turns axially between the vanes and the runner and then enters the runner. According to whether the rotor blades can be rotated in operation, the axial flow turbine is divided into two types: axial flow fixed type and axial flow rotary type. The axial flow rotary hydropower unit has a lower water head, so the single unit capacity is relatively small. Up to now, it was put into operation in the early 1990s. The largest actual operating power of 220 kW of Shuikou Hydropower Station, which was manufactured by Hitachi and Harbin Electric Machinery Co., Ltd., is still the world's largest single-unit axial-flow rotary hydropower unit. The 170 MW unit of the Gezhouba Hydropower Station, designed and manufactured by Dongfang Motor Co., Ltd., is the world's largest axial-flow rotary-type hydropower unit. Its main parameters are rated power of 170 MW, rated speed of 54.6 r/min, stator diameter of 20 m and rotor diameter of 16.948 m.

2.3. Pumped storage hydropower unit
When the power in the grid is low, the power from the lower reservoir is pumped to the upper reservoir to store energy. When the grid is under peak load, the hydropower station that returns to the lower reservoir to generate electricity is also called an energy storage hydropower station. China's first 11 MW pumped storage unit was put into operation in 1968. Due to the lack of technology at the time, it developed nearly stagnant in the next 20 years. With the rapid development of social economy brought about by reform and opening up, China attaches great importance to the development of clean energy. By the end of 2017, 97 sets of pumped storage units with a total installed capacity of 25,250 MW and 40 MW and above have been put into operation [8-11].

2.4. Tubular hydro-flow unit
The cross-flow turbine is a horizontal-shaft turbine with a straight flow path. The runner is similar to the axial flow, and can be made into two types: fixed slurry and rotary slurry. The main advantages of
the cross-flow turbine are: the water flow is basically in the axial direction, does not turn, improving the efficiency and over-current capability; because the flow path is shaped like a pipe and the main shaft is lying, the height, spacing and simplified hydraulic structure of the plant can be shortened. Reduce the amount of civil works. Up to now, China's single-machine maximum cross-flow hydropower unit is 58 MW of the Daping River Shaping II Hydropower Station.

2.5. **Impact hydropower unit**

The impact turbine is suitable for high-head, low-flow power stations. The water from the pressure pipe is converted into a high-pressure jet through the nozzle, and the tangential impact wheel rotates to drive the rotor to generate electricity. Impact hydropower unit in China's development is relatively slow, in the early 21st century into operation, by the Oriental Electric Co., Ltd. and Vio technology Otis Company to manufacture the single-machine capacity of the Golden Nest Hydropower station 140 MW, the maximum head 619.8 meters of the unit for China's largest single-machine capacity impact hydroelectric unit.

2.6. **Installed composition**

379 sets of 40-99 MW units, with a total capacity of 22872.28 MW, accounting for 10.8% of the total installed capacity of hydropower; 209 units of 100-199 MW, with a total capacity of 28496 MW, accounting for 13.46% of the total installed capacity of hydropower; 111 units of 200-299 MW units, total capacity 25998.88 MW, accounting for 12.28% of the total installed capacity of hydropower; 122 units of 300-399 MW, with a total capacity of 38384.5 MW, accounting for 18.13% of the total installed capacity of hydropower; 150 units with capacity of 400 MW and above, with a total capacity of 95990 MW, accounting for the total installed capacity of hydropower 45.33%, as shown in figure 1.

![Figure 1. Capacity composition of hydropower units in the 2017.](image_url)

3. **Running conditions**

The operation of various types of hydropower unit in 2013-2017 is shown in table 1.

In recent years, with the continuous improvement of the manufacturing and installation of China's hydropower units, the level of operation, maintenance and management has also improved, and the operational reliability level of the units has also maintained steady growth. In 2017, the average equivalent available factor of hydropower units was 92.55%, an increase of 0.11% year-on-year; the average annual available hours of hydropower units was 3747.51 hours, an increase of 30.32 hours compared with the same period of last year; in 2017, 213 units were added compared with 2013, of which The number of axial flow units has increased by 9, and the number of mixed flow units has increased by 188. The number of pumped storage units has increased by 16 units; the available hours have increased by 490.57 hours, of which the axial flow units have increased by 199.53 hours, and the mixed flow units have increased by 387.04 hours. The number of units can be increased by 1646.86 hours; it can be seen that the hydropower units in China are generally operating well.
Table 1. Operation of various types of hydropower unit in 2013-2017.

| unit classification         | year | number of statistics stations | available hours | equivalent available factor (%) |
|-----------------------------|------|-------------------------------|-----------------|----------------------------------|
| axial flow hydropower unit  | 2013 | 140                           | 4085.56         | 92.66                            |
|                             | 2014 | 140                           | 4423.05         | 93.35                            |
|                             | 2015 | 144                           | 4569.97         | 92.75                            |
|                             | 2016 | 151                           | 4555.49         | 93.14                            |
|                             | 2017 | 149                           | 4285.09         | 92.24                            |
| mixed-flow hydroelectric unit | 2013 | 537                           | 3495.84         | 91.62                            |
|                             | 2014 | 602                           | 3727.96         | 92.85                            |
|                             | 2015 | 656                           | 3743.33         | 92.38                            |
|                             | 2016 | 709                           | 3725.79         | 92.76                            |
|                             | 2017 | 725                           | 3846.88         | 92.99                            |
| pumped storage hydropower unit | 2013 | 81                            | 1281.90         | 91.57                            |
|                             | 2014 | 85                            | 1537.85         | 90.50                            |
|                             | 2015 | 85                            | 1801.18         | 89.18                            |
|                             | 2016 | 85                            | 3035.11         | 89.45                            |
|                             | 2017 | 97                            | 2744.76         | 89.75                            |
| total                       | 2013 | 758                           | 3256.94         | 91.71                            |
|                             | 2014 | 827                           | 3520.44         | 92.60                            |
|                             | 2015 | 885                           | 3593.33         | 92.05                            |
|                             | 2016 | 945                           | 3717.19         | 92.44                            |
|                             | 2017 | 971                           | 3747.51         | 92.55                            |

4. Planned outage analysis

The planned outage of hydropower unit in 2013-2017 is shown in figures 2 and 3.

![Figure 2](image1.png)  
**Figure 2.** Number of planned outages of hydroelectric units in 2013-2017.

![Figure 3](image2.png)  
**Figure 3.** 2013-2017 hydropower unit planned outage time.

From 2013-2017, the number of planned outages for all units in 2017 was 2.11 times per unit year, a decrease of 0.07 times per unit year compared to 2013, of which the number of planned outages for axial flow units was 1.66 times per unit year, an increase of 0.02 times per unit year over 2013; The number of planned outages for mixed-flow units was 1.45 times per unit year, a decrease of 0.23 times per unit year from 2013, and the number of planned outages for pumped storage units was 7.7 times per unit year, an increase of 1.4 times per unit year over 2013.

From 2013-2017, The planned outage time for all units in 2017 was 641.67 hours, a decrease of 66.98 hours from 2013, of which the planned outage time for axial flow units was 678.14 hours, an increase of 44.62 hours over 2013, and the planned outage time for mixed-flow units was 602.16 hours, a decrease of 115.7 hours compared with 2013; The planned outage time for pumped storage units was 884.81 hours, an increase of 174.63 hours over 2013.
In general, the number of planned outages and planned downtime of hydroelectric units showed a downward trend, among which, the number of planned outages and planned downtime of mixed-flow units was the lowest, the number of planned outages of axial flow units and the planned outage time were relatively stable year by year, and The planned shutdown times and planned outage time of pumped storage units are much higher than the national average, and it can be seen that how to arrange the maintenance time and period of pumped storage units reasonably plays a key role in reducing the number and time of planned outages of the whole hydroelectric unit, thus further improving the equivalent reliability level of the whole hydroelectric unit.

5. Unplanned outage analysis
The unplanned outages of various types of hydropower units in 2013-2017 are shown in Table 2.

| Unplanned Outages of Various Types of Hydropower Units in 2013-2017. |
|---------------------------------------------------------------|
| **unit classification** | **year** | **number of statistics stations** | **number of unplanned outages (times/year)** | **unplanned outage hours** |
|-------------------------|---------|----------------------------------|------------------------------------------|---------------------|
| Axial flow hydropower unit | 2013    | 140                              | 0.19                                     | 9.81                |
|                         | 2014    | 140                              | 0.13                                     | 2.10                |
|                         | 2015    | 144                              | 0.11                                     | 0.78                |
|                         | 2016    | 151                              | 0.13                                     | 1.07                |
|                         | 2017    | 149                              | 0.10                                     | 1.89                |
| Mixed-flow hydropower unit | 2013    | 537                              | 0.14                                     | 7.70                |
|                         | 2014    | 602                              | 0.09                                     | 7.17                |
|                         | 2015    | 656                              | 0.09                                     | 3.83                |
|                         | 2016    | 709                              | 0.07                                     | 3.92                |
|                         | 2017    | 725                              | 0.05                                     | 7.97                |
| Pumped storage hydropower unit | 2013    | 81                               | 2.20                                     | 28.57               |
|                         | 2014    | 85                               | 2.05                                     | 26.08               |
|                         | 2015    | 85                               | 1.98                                     | 17.33               |
|                         | 2016    | 85                               | 2.08                                     | 11.33               |
|                         | 2017    | 97                               | 1.33                                     | 12.80               |
| Total                  | 2013    | 758                              | 0.37                                     | 10.70               |
|                         | 2014    | 827                              | 0.30                                     | 9.04                |
|                         | 2015    | 885                              | 0.27                                     | 5.08                |
|                         | 2016    | 945                              | 0.26                                     | 4.48                |
|                         | 2017    | 971                              | 0.19                                     | 8.09                |

Figure 4. Unplanned outage reliability index for hydropower units in 2016-2017.

As shown in Figure 4, in 2017, there were 179 unplanned outages of 971 hydropower units nationwide. The total unplanned outage was 12558.99 hours, and the average annual number was 0.19
and 8.09 hours respectively. The annual average number of unplanned outages decreased year-on-year 0.05 times, but the unplanned outage time increased by 3.61 hours. Among them, the first three types of unplanned outages, namely forced outages, occurred 138 times, and the total time of forced outages was 11,601.21 hours, accounting for 77.09% and 92.37% of the total number of unplanned outages, respectively. It can be seen from table 2 that from 2013 to 2017, the number of unplanned outages of all hydropower units decreased year by year, while the non-planned outage time showed a concave trend, and the minimum number of unplanned outages in 2016 was 4.48 hours. Among them, the number of unplanned outages of axial flow units, mixed flow units, and pumped storage is also basically decreasing year by year, and the number of unplanned outages of pumped storage units is higher than that of other types of units.

5.1. Device cause analysis
In the main equipment of the hydropower plant, the average number and time of unplanned outages caused by the turbine are 0.02 and 0.84 hours respectively, and the cumulative outage time accounts for 6.57% of the total unplanned outage; the average annual number and time of unplanned outages caused by Transformers were 0.00 and 0.79 hours, respectively, and the cumulative outage time accounted for 6.16% of the total unplanned outage time; the average number and time of unplanned outages caused by the generator are 0.02 times and 0.35 respectively, and the cumulative outage time accounted for 2.72% of the total unplanned outage time, see table 3.

| ranking | master device | unplanned outage hours | Percentage (%) |
|---------|---------------|------------------------|----------------|
| 1       | turbine       | 0.84                   | 6.57           |
| 2       | transformer   | 0.79                   | 6.16           |
| 3       | generator     | 0.35                   | 2.72           |

5.2. Analysis of reasons for responsibility
The three reasons for the unplanned outages are external causes, poor product quality, and poor construction and installation. Among them, the external cause of the unintended outage was the first, the average number of times in the year was 0.00, but the unplanned outage time caused by it reached 9.44 hours/year, accounting for the total unplanned outage time. 73.47%; followed by poor product quality, the average number and time of unplanned outages were 0.10 and 2.29 hours respectively, and the cumulative outages accounted for 17.86% of the total unplanned outage time; the third is The average installation times and time of unplanned outages caused by poor construction were 0.02 and 0.38 hours respectively, and the cumulative outages accounted for 2.94% of the total unplanned outages, as shown in table 4.

| ranking | reason for responsibility | unplanned outages | unplanned outage hours | Percentage (%) |
|---------|---------------------------|-------------------|------------------------|----------------|
| 1       | external causes           | 0.00              | 9.44                   | 73.47          |
| 2       | poor product quality      | 0.10              | 2.29                   | 17.86          |
| 3       | poor construction installation | 0.02          | 0.38                   | 2.94           |

5.3. Operational reliability of newly commissioned hydropower units
In 2016, the hydropower unit that was put into operation in 2016 participated in the reliability evaluation of 26 units with a total capacity of 7624 MW. In 2017, the equivalent availability factor was 89.66%, a decrease of 4.6% year-on-year; the number of unplanned outages was 0.85 times/year, up 0.69 times per year, as shown in table 5. The equivalent of the hydropower unit was put into operation in 2016. The available coefficient is lower than that of hydropower units put into production...
in other years from 2012 to 2015. It is due to the planned maintenance of 88 new units in 2017, including 5 major repairs, accounting for 5.68%, as shown in table 5.

Table 5. Reliability index of new production units in the past 5 years.

| evaluation year | production year | number of statistics stations | average capacity (MW) | service factor/ (%) | equivalent available factor / (%) | equivalent forced outage rate / (%) | number of unplanned outages (times/year) |
|-----------------|-----------------|-------------------------------|-----------------------|---------------------|----------------------------------|-----------------------------------|-------------------------------------|
| 2017            | 2016            | 26                            | 293.23                | 48.77               | 89.66                            | 0.16                              | 0.85                                |
| 2016            | 2015            | 44                            | 192.63                | 55.28               | 94.26                            | 0.04                              | 0.16                                |
| 2015            | 2014            | 48                            | 329.44                | 57.07               | 91.91                            | 0.29                              | 0.10                                |
| 2014            | 2013            | 61                            | 404.55                | 58.34               | 93.91                            | 0.18                              | 0.38                                |
| 2013            | 2012            | 39                            | 353.85                | 64.30               | 91.04                            | 0.32                              | 0.94                                |

5.4. Operational reliability of 700 MW hydropower units
In 2017, 700 MW hydropower units had three unplanned outages. The average average of unplanned outages was 0.04 and 0.94 hours. In these three non-stops, the hydroelectric generators were triggered twice. The auxiliary equipment of the power plant is triggered once, as shown in table 6.

Table 6. Main operational reliability indicators of 700 MW hydropower units in the past five years.

| year | number of statistics stations | number of unplanned outages | equivalent available factor (%) | equivalent forced outage rate (%) |
|------|-------------------------------|------------------------------|---------------------------------|----------------------------------|
| 2017 | 76                            | 0.04                         | 94.88                           | 0.01                             |
| 2016 | 76                            | 0.04                         | 95.23                           | 0.02                             |
| 2015 | 76                            | 0.04                         | 94.57                           | 0.01                             |
| 2014 | 68                            | 0.06                         | 94.42                           | 0.00                             |
| 2013 | 53                            | 0.19                         | 92.55                           | 0.01                             |

6. Analysis of main problems
- The utilization hours and unplanned outage times and time of pumped storage units are lower compared to other types of hydropower units, and the number of unused hours is relatively low, so the pumped storage units are strengthened. Reliability management is very necessary.
- The equivalent available coefficient and the number of unplanned outages for the newly commissioned units in 2016 are lower than the equivalent annual available coefficients for other hydropower units put into operation, rather than the planned number of outages and time, so the new production unit should strengthen strict management of planning, design, product quality, installation, commissioning, operation management, maintenance and other aspects to ensure the reliability level of equipment.
- Strengthen the monitoring of unplanned outages of hydropower units and systems. To realize the intelligentization of hydropower system, higher requirements are put forward for the control and detection technology of hydropower units, fault diagnosis and early warning system [12], and the optimal allocation of hydropower resources. By installing the monitoring system to find out problems in the running process in a timely manner, solve the problem in a short time and ensure that the hydropower unit is operating normally.
- Reducing the project cost of the hydropower unit power generation project unit. In 2017, the average cost of hydropower units was 11,360 yuan/kW, an increase of 3.4%; and the unit cost of a 1 million kilowatt coal-fired power generation project was only 3232.5 yuan/kW, and other non-fossil energy power generation projects cost land on the wind of 7719 yuan/kW, concentrated Photovoltaic power generation is 7258 yuan/kW, which is lower than the construction cost of hydropower units. The high construction cost of hydropower units is due to the gradual reduction of economically developable water resources, the difficulty of
development and the rising cost.

7. Conclusion

- China is not only the world's largest hydropower installed country, but also the country with the largest scale and fastest development. It has gradually become the center of world hydropower innovation [13]. However, compared with the famous foreign power generation equipment manufacturing companies, there is a clear gap between the complete set of pumped storage units and the system integration design. There are still many gaps in the core manufacturing equipment and technology, which is also the key direction to improve the reliability level of pumped storage units in the future.

- Hydropower has become the second largest power generation source for thermal power in China. It is also the third generation power generation with a newly installed capacity of 12.87 million kilowatts in 2017, which is second only to solar energy of 53.41 million kilowatts and thermal power of 44.53 million kilowatts. Therefore, the operational reliability of hydropower units is important for the sustainable development of the grid and the hydropower market.

- In order to ensure the stable operation of the hydropower unit, it is necessary to regularly repair and maintain the hydropower unit equipment [14, 15]. Advanced technology should be used to monitor the status of the hydropower unit, which helps the plant management personnel to maintain in time to avoid over-repair or owed repair.

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