Developments and characteristics of pumped storage power station in China

Y W Xu¹ and J Yang²

¹ State Grid Xinyuan Company Ltd., Beijing, China.
² Technology Center, State Grid Xinyuan Company Ltd., Beijing, China

yangjingshirley@163.com

Abstract. Pumped-storage can quickly and flexibly respond to adjust the grid fluctuation and keep the grid stability because of its various functions. Besides, it is an effective power storing tool and now it has become the largest and most widely used energy storage form. Many countries configured a certain proportion of pumped storage power in the network to keep their grid stability. This paper introduces the current development status of the pumped storage power (PSP) station in some different countries based on their own economic demands and network characteristics. Then the evolutions of the pumped-storage power station in China are focus reviewed. To provide better technical support for future PSP development, the typical features of the PSP in plant design, construction, operations, and economic evaluation are described in detail compared with the conventional hydropower plant. The difficulties and challenges of the pumped storage technology faced in China are also summarized and the future development directions are prospected.

1. Introduction

Conventional hydraulic power station is mainly used to produce electricity. There are many roles for pumped storage power station like balancing the power generation and consumption, adjusting frequency and phase, quickly black start-up and providing standing reserve for electric power system. So it can be seen as an effective grid adjustment tool, which is indispensable for constructing the “strong and intelligent” grid. Besides, the world is in a critical transition period from traditional fossil energy to clean and renewable energy, and PSP plays an important role in it. PSP can not only preserve the energy generated by renewable energy source and regenerate it later when needed, but also adjust the grid stability aroused by intermittent energy source in-grid. For example, the electric system instability in Europe is resolved by PSP, so PSP is also called “green battery” [1]. It is meaningful for the reality of the sustainable development. What’s more, PSP can reduce the regulate depth of the thermal power at peak time and improve the turbine operating efficiency. Many countries in the world are actively promoting the PSP development in recent years. It has been specified as the key working direction of the international hydropower industry in 2016 [2]. The new added PSP capacities are 6.4GW in the worldwide in 2016, which close to the twice of that in 2015 [3]. These indicate the importance of PSP in the electric system has been increasingly recognized.

The problems of limited energy total amount, uneven energy source distribution, serious environment pollution and lower energy usage efficiency are highlighted in China. With the economy development, the electricity demands and the power quality requirements are getting higher and higher,
which vigorously promotes PSP to be the important supporting measure for our country’s sustainable development [4] and it has been written to many energy power development plans [5]. For example, the state “13th five-year plan for energy development”, “13th five-year plan for new energy development”, “13th five-year plan for electric development”, “13th five-year plan for hydroelectric development”, all of them proposed the aim, planning and key tasks. The fast progress of PSP in our country in the next few years can be foreseen.

This paper concludes the PSP development in China and analyzed the typical characteristics of PSP compared with the conventional hydropower. Besides, the puzzles faced during the PSP construction are summarized, and the future development directions are prospected.

2. Pumped storage developments in some countries

As stated above, many countries are planning and constructing the PSP stations. The installed capacity and its proportions in the total electric system in some countries are shown in table 1.

| country      | installed capacity (MW) | Total capacity (MW) | Proportion (%) |
|--------------|-------------------------|---------------------|----------------|
| Japan        | 26270                   | 292060              | 9              |
| Italy        | 7540                    | 118450              | 6.4            |
| Korea        | 4700                    | 84650               | 5.6            |
| France       | 6990                    | 131360              | 5.3            |
| Spain        | 5260                    | 102800              | 5.1            |
| Norway       | 1330                    | 31690               | 4.2            |
| Germany      | 6780                    | 163260              | 4.2            |
| Poland       | 1410                    | 34550               | 4.1            |
| England      | 2740                    | 93820               | 2.9            |
| America      | 22290                   | 1055280             | 2.1            |
| China        | 21530                   | 1257580             | 1.7            |
| Australia    | 740                     | 61120               | 1.2            |
| Sweden       | 100                     | 35230               | 0.3            |
| Canada       | 180                     | 138690              | 0.1            |

It can be seen a very large differences in the installed capacity and proportions exist in different countries, even for the developed countries. That relates to the specific situations and development stages of a country’s electric system, and the main reasons can be obtained from the grid environment, power source structure and grid manage mode.

1) The grid environment demands for PSP are different.

The grid in island country needs large amount of PSP to adjust the electricity balance, for example, Japan and Korea. The installed capacity of PSP in Japan exceeds America from the 1990’s, and now the electric system has the highest PSP proportion in Japan [6], and the proportion is 9% by the end of 2014. Besides, for the countries with weak grid connection to the outside also need more PSP to keep their grid stability, for example the Peninsula italiana, Iberian Peninsula.

2) The grid power source structure requirement for PSP is different.

As is known to all, the hydroelectric itself has strong ability to adjust the output. Thus, the countries with higher hydroelectric proportions demand less PSP, for example Norway, Australia, and Canada et al. The countries mainly depending on oil and gas power source also need less PSP because of their flexible adjustment ability. On the other side, the thermal power and nuclear power based grid needs more PSP to enhance the flexibility of the grid, because the thermal power regulation ability is weak and the nuclear power usually operated as base load. For example, the PSP is also vigorously developed at the same time with the nuclear power, which is largely promoted in 1970’s in France. What’s more, the wind and solar power belong to the intermittent and unstable power source, the generation electricity can be well balanced with a certain proportion of PSP installed in the electric system.

3) The needs of grid management mode for PSP are different.
The electric product quality is the supplement quality. In some countries like Japan and France, the electricity price is related to the electricity quality, which means the grid reaction speed has to be considered to guarantee the reliability electricity supplement as a failure occurs in grid. Besides, the countries with higher peak and valley electricity price differences, like 5:1 in Italy, 10:1 in France and 3:1 in China, have more PSP constructing enthusiasms because of the higher income in these countries.

3. Pumped storage evolutions in China

In May 19th, 2017, the Liyang pumped storage power station in Jiangsu province put into production, then the total PSP installed capacity in China has reach to 27690 MW, which surpass the 27640 MW installed capacity in Japan, and China becomes the world’s largest PSP installed capacity country. Till now, the PSP development in China has gone through five stages, they are start stage, stagnation stage, breakthrough stage, forming the scale stage, rapid development stage. The situations in each stage are briefly introduced as follows.

(1) Start stage

Compared to the developed countries, PSP started late in China. Until to the late of 1960’s, our country began to study and plan the PSP station. Then the Hebei Gangnan (1 unit, 11MW) and Beijing Miyun (2 units, 11MW) hybrid PSP stations were successively built. But the capacities of the units are so small that the role and benefit of PSP cannot fully reflect in the electric system.

(2) Stagnation stage

The PSP was vigorous expansion in 1970~1980 in aboard. However, it was stagnant in China. There are three reasons for the stagnation. Firstly, our country faced an electricity shortage situation from 1970, building the conventional power station to resolve the electricity shortage problem is much more important at that time. Second, the PSP construction enthusiasm is insufficient under the policy of single electricity price at peak and valley periods for a long time. Last but not the least, the attention for the electricity quality is less in the early time.

(3) Breakthrough stage

With high-speed development of national economy after China’s reform and opening up in 1990’s, the electricity consumption keeps climbing, which leads to the changes of the grid load structure, the peak and valley differences are larger and larger. In some region grids presented serious peak electricity shortage, like the east of China, north of China, north east of China and Guangdong. Under this situation, PSP technology achieved a breakthrough because of its flexible and fast peak regulation ability. Large scale of PSP stations are constructed in that period, for example Panjiakou, Guangxu, Shisanling, Xikou, Xianghongdian, Yangzhuyong, Tianhuangping PSP stations and so on.

(4) Forming the scale stage

After entering the 21st century, the contradiction between the peak and valley electricity requirements became increasingly prominent. That led to the power limit at the peak period in a large area of China. Under this background, five power generation groups were established to ease the contradiction of electricity supplement. Thermal power and nuclear power obtained a rapid development at this period. However, these power sources further increased the grid regulation difficult. The grid demand for PSP obviously increased and the constructions of PSP quickly sped up, a large number of PSP stations were built, like Tongbai, Yixing, Taian, Baoquan, Huilong, Bailianhe, Huizhou, Zhanghewan, Xilongchi, Langyashan, Pushihe, Xiangshuijian and Xianyou PSP stations.

(5) Rapid development stage

With the deepening of reform and opening up in China, the environment protection problem is proposed to simultaneously promote with the economic development. The installed capacity of the intermittent wind and solar clear power sources quickly increased. Besides, the ultra-high voltage transmission has been widely used. The grid situations are more and more complex. Accelerating the PSP development to guarantee the grid stability and improve the electricity quality has become the important grid construction aim.

Both of China’s “12th five-year plan for electric development” and “13th five-year plan for electric development” put the PSP development as a focus. Till to the end of 2016, the total installed
capacity of PSP in China has reach to 26700MW, and the building capacity has reach to 32000 MW. All of the total capacity of the built and under construction, the biggest capacity in a single station, the largest single unit capacity and the highest rated head of unit are located in the forefront of the world.

The document of China’s national development and reform commission [2014]2482《several opinions on promoting the PSP healthy and orderly development》proposed the PSP development aim, the total PSP installed capacity need to reach to 100,000 MW till to 2025, and the proportion in the electric system should reach to about 4%. Based on this plan, there are nearly 73000 MW PSP still needs to be put into construction in our country, since then the PSP really enters into the rapid development stage.

4. Characteristics of Pumped storage power station
The PSP development time in China is not long enough, the project management mainly attributes to hydroelectric industry. Thus, most of the technical standards and specifications in hydroelectric industry are used in PSP projects. However, after 20 years experiences accumulating in construction and operating, the large gaps have been proved exist between PSP project and the conventional hydroelectric project in planning, designing, construction, operating and maintenance stages. Therefore, the specific PSP station designing and construction methods should be adopted based on its characteristics during the rapid advance process.

4.1. PSP planning stage
In the planning stage, many influencing factors need to be comprehensively considered to judge whether or not to build the PSP station. The comprehensive analysis should be conducted to determine the optimal site, the main technology parameters by considering the region economic and energy source development state, electric system composition and requirement, regional geological condition, water source, environment and so on.

The electric system demand should be the precondition of the location planning. The construction necessarily needs to go through deep and detail analyses and arguments.

The PSP station site planning has two stages, which are site search and the site selection. In the site search stage, the proper locations used to build the PSP stations are preliminary formulated by explorations on site. During the pump-turbine operation, the water is only recycled instead of consuming. Thus the height difference between the upper and lower reservoirs is the primary concerning aspect in the site planning. After exploring the conditions of the alternative site, topography, geology, water source, sediment, reservoir submerged and environment effects, the proper site is selected as the search one. In the site selection stage, the construction conditions will be further analyzed in detail, the capacity need to meet the grid requirement and the location needs to close to the electricity load center. Based on the results of site search, the site with better comprehensive conditions, which conclude small distance and height ratio, better topography and geology conditions, smaller environment impact and reservoir submerged range and so on, will be selected as the planning site.

All of the parameters mentioned above have direct relate to the PSP station construction economy and operation stability. For example, the water delivery passage will be short for the site with small distance and height ratio, which means the better stability in the transient process and higher utilize efficiency. The location with larger accumulated rainwater area in upper reservoir can product higher manages profit. The higher daily generation hours means the better adjustment performance of the PSP station but higher construction cost. The price mechanism has nothing to do with the PSP daily generation hours in our country at present. The designed daily generation hours have large differences in the operated PSP station. For example, the daily generation hours of Bailianhe PSP station is 2.2 hours, but it is 11 hours in Hongping PSP station.

4.2. PSP design stage
To guarantee the safety, stability and efficiency of the PSP station, the specific characteristics of the PSP station need to be considered in the design stage.

(1) Design safety standard.

For conventional hydroelectric station, the project scale determined by installed capacity is consistent with the reservoir efficiency storage capacity. However, the reservoir storage capacity in PSP station is always smaller than the conventional hydroelectric station, which leads to large differences between the results determined by installed capacity and the reservoir storage capacity.

The technology standard *Classification and design safety standard of hydropower project (DL5180-2003)* says: For the PSP station with large installed capacity but small reservoir storage capacity, the flood design criteria for the retaining and draining buildings can be determined by the level of the powerhouse if the project crash has little effect on the downstream. Otherwise, the retaining and draining buildings should be designed according to the retaining and draining buildings standard requirements in hydroelectric project. But the flood standards of the corresponding standard building need to be satisfied for the station with larger reservoir storage capacity. We should deal with projects case by case in the design stage. Usually, the scales of the most projects are determined by installed storage [8].

(2) Pump turbine design

In order to pursue better economy, the higher rated head always been selected. In China, the rated head in the most of the PSP stations exceeds 200 m, and the maximum head already proximate 800 m. The reservoir water level drop depth in each day is larger than 20 m. Under this condition, improving the unit stability and cavitation performance at the generating and pumping conditions are the key points in the pump turbine design stage [9]. What’s more, the pump turbine also requires distinct design schemes to meet the frequently start and stop and bidirectional rotation operating characteristics.

(3) Water delivery system safety of a tunnel with multi-units

The water delivery system of PSP station is usually longer than the conventional hydroelectric station, which leads to the higher penstock cost. The multi-units in a hole scheme is usually adopted for the water delivery system to control the project cost, for example four units in one tunnel. This scheme brings a disadvantage for the transient process stability. The dynamic interference of the other units may occur as one unit transfer operation condition in the same tunnel. The transient process stability can be controlled for one tunnel with two units at present. However, to avoid the unpredicted dangerous, the load rejection test for one tunnel with four units is extremely rare on site. The debates always exist for the load rejection test of four units in one tunnel at the same time. The technology standard *Specification for start-up test of reversible pumped-storage units (GB/T 18482-2010)* and other related criterions have not stated expressly for this issue [10]. But Qingyuan PSP station successively conducted the load rejections test of four units in one tunnel at the same time in the last year, the results can provide experience and reference for the field test and similar power station construction in the future [11].

(4) Upper reservoir anti-seepage treatment

Most of the upper reservoirs have less natural water source, besides, the upper reservoir area is small with only 1~2 square kilometers. That means the water needs to be pumped to the upper reservoir from the lower reservoir by consuming electricity. Thus, more attentions to the anti-seepage design of the upper reservoir need to be paid in the PSP station design. At present, the anti-seepage treatment concludes many modes, like the concrete panel, curtain grouting, geomembrane, asphalt concrete, clay heart wall and so on. However, the clear technical regulation for the application of the anti-seepage treatment mode is still lack.

(5) Design of freeze-thaw in cold area

The water level drop depth of the reservoir is larger than 20 meters each day. For the reservoir safety operation, the freeze-thaw design in winter is another key point needing to be considered. All of the concrete freeze-thaw selecting, expansion joint seal fastening style and slope protection design need to be analyzed in detail in the design stage.
4.3. Characteristics in construction stage

During the construction of PSP station, there are four aspects distinct to the conventional hydropower station according to the author’s experiences.

(1) Underground caverns intensive

The PSP station is basically designed as underground plant considering the suction height requirement at pumping condition. All of the water delivery system, traffic system, ventilation system, drainage system, voltage regulation system building around the powerhouse are composed by underground caverns. The underground caverns construction has narrow working area, large amount of blasting, complex geological conditions, lots of mutual interference factors features. Besides, many working area are engineering key routines. Therefore, scientific and rigorous construction organization design needs to be conducted.

(2) Water delivery system construction

The length of the water delivery system in PSP station is longer and the height difference is larger. So the shaft or inclined shaft schemes must be adopted in the construction. But the constructions face many difficulties for the shaft or inclined shaft higher than 200 meters. What’s more, the steel penstock is usually used for the water delivery system. This makes the construction of the water delivery system becoming the unique focus and difficult part.

(3) Inconsistent excavation and utilization time of earthwork

The sand gravel aggregate used in the PSP station construction is usually obtained from the engineering excavation material with further process. But in general, the excavation peak of the aggregate is earlier two years around than the utilization peak period, which brings a series of construction problems distinct to the conventional hydropower station. The issues about the excavation materials keeping, balancing, transport, utilization and the process system design and so on need to be planned ahead of time.

(4) Complex unit commissioning process

The commissioning of the conventional hydro turbine is usually conducted by the construction unit with the completion work of the manufacturer. But the conditions of the pump turbine unit are much more complex, so does its commissioning process. The dynamic balance characteristics and the first turbine start-up mode are highly related to the engineering cost, the local grid stability accessed during the commissioning period and the unit operating safety and stability. In a word, it needs more professional PSP testing staffs to carry out unit commissioning.

4.4. Operation and maintenance features

The pump turbine structure is much more complicated compared with the conventional hydropower unit. To meet the grid demands in time, the pump turbine has to frequently start-up or shutdown or transfer conditions. That also puts forward the response speed requirements for the auxiliary systems. Because of these characteristics, the operation and maintenance works in PSP station are much heavier.

Besides, there are also many differences in the operation and maintenance way in different power grid. That is due to the different internal management modes of the pumped storage company and power grid service requirements to the pumped storage unit. For instance, the integration mode of operation and maintenance is adopted by state grid xinyuan Co. Ltd, while the southern grid adopts the on-call operation mode.

4.5 Economic evaluation method

The conventional hydropower station is mainly used to generate electricity, so it can be evaluated directly by the electricity. Whereas, the specific services provided by PSP station are much more than conventional hydropower station to maintain the power grid stability. Thus, the economic evaluation for pumped storage power station is more complex, which should be discussed and determined according to its function.
For instance, the different peak and valley electricity prices are applied for the peaking and valley-filling services. At present, the price difference between the peak and valley period on the user side is about three times in China. While, the electricity price on the generation side is based on the benchmark price or the approved electricity price, without considering the peak valley difference and the bidding price modes. After the formation of the electricity market in the future, the bidding price mode will be put into use, and the power generation companies should also consider the peak valley difference. According to the principle of the electricity directly supplied to large user, pumped storage power stations can directly purchase electricity from the power generation company at the low electricity consumption period with lower price, and then regenerate electricity and sell it at the peak period with higher prices. Generally, if the price difference at peak and valley periods is greater than 5 times, and the annual power utilization hours reach to the design value, the PSP station can basically realize the balancing of the income and normal operation cost according to the preliminary calculation.

At present, all province electric power companies have set up the corresponding auxiliary service requirements for the power supply enterprises in grid based on the respective regional power grids characteristics. The better profit can be acquired by PSP because of its good auxiliary services. But the economics of the auxiliary services are still not fully reflected under the current power system.

After the electricity market formation and the electric power system reformation in our country, China is going to adopt the benchmark price for pumped storage capacity and determine the pumping electricity price and the generating electricity price through the bidding way. With the rapid development of new energy source, the electric power system reformation depth and the formation of the electricity market, the role of pumped storage will become increasingly prominent, it will brings more comprehensive function for grid, and its economy will be more and more outstanding.

5. Difficulties in Pumped Storage Technology
PSP technology has only developed several decades in our country and the experience accumulation of PSP is even less than twenty years after the scale construction. Today, the PSP still faces many technology puzzles although the system and equipment of the PSP station are keeping improving. The applicability of each technology standard, the advanced nature of the technology parameters and the reasonability of engineering construction technology are still worth discussing. Here only present some common problems to be solved recognized by the authors.

(1) Pump turbine design suitable for large capacity and high head.
Since obviously advantages in terms of lower construction cost and higher unit operation efficiency, the PSP stations with large capacity and high head are the main development trend in the future [12]. Whereas, the large capacity and high head also lead to longer water delivery passage, higher rotation speed and complex transient process. These characteristics put forward higher requirements for unit design. But the design and manufacture experiences are still insufficient whether at home or abroad.

(2) Research on variable speed pump turbine unit
The adjustment range and performance of variable speed pump turbine are further increased than the fixed speed unit due to their wide operation range and operating flexibility. It can actively regulate the grid power and improve the consumption flexibility of the intermittent power source to keep the grid stability. The research on variable speed pump turbine started at 1960’s in aboard, while it still in start stage in china, more systematic and depth explores are still needed to meet the grid stability requirements during the ultra-high voltage transmission development process[13].

(3) Whether the ball valve involves in the transient process adjustment or not
Since the PSP technology of Alstom is introduced in Baoquan, Huizhou, Bailianhe PSP stations, the ball valve involving in the transient process adjustment always happens to control the pressure rise at the spiral casing inlet lower than the designed guarantee value [14]. As is known to all, the ball valve is designed to hold water using its spherical surface, the abrasion may present at the spherical surface as the flow goes through during the ball valve opening or closing process, which will no doubt affects the seal ability of the ball valve. Thus, the ball valve is only recommended to open or close in static
water. The ball valve involving in the transient process adjustment means the design levels of the PSP unit and water delivery passage need further improving.

(4) Pressure pulsation effect on the spiral casing inlet design pressure

The spiral casing inlet design pressure is the important parameter in the unit bidding documents, which is the key design parameter for the manufacturer. This value is usually obtained through one-dimensional transient process simulation. The pressure fluctuation amplitude in load rejection process is huge based on the transient process tests. But the simulation results can only provide cross section average pressure at the spiral casing inlet and draft tube inlet, the pressure fluctuation effects cannot be reflected. Besides, the pressure fluctuation level is directly relate to the hydraulic design result, but the hydraulic design level of different manufactories exist a certain differences and the design differences even also exist in the different projects designed by the same manufacturer. The designing institutes only provide a conservative value based on the experiences, lacking of theoretical and practical data supports. That is to say, how to consider the pressure fluctuation effect is still not sure at present. Therefore, the reasonable pressure fluctuation value is worth to be studied to improve the accuracy of transition process prediction.

(5) Cavitation design criteria at the draft tube inlet.

This item affects the engineering structure arrangement and the project cost. According to the current design specification, the maximum vacuum value at the draft tube inlet should not less than 0.08 MPa for the conventional hydropower unit. Considering the complex operation conditions, no negative pressure is designed as the maximum vacuum guarantee value for the pumped turbine. It can be seen a large difference for the two types of power stations although both of the generating conditions are considered. Apparently, the draft tube inlet vacuum guarantee value of pumped storage unit is conservative, but how to exactly determine the vacuum guarantee value based on the operating characteristics of pump turbine remains to be studied.

(6) Stress proportion shared by surrounding rocks in water delivery system.

The water delivery system is longer in the pumped storage power station, and the high-pressure penstock design length is correspondingly longer. The penstock is arranged in the ground and contacted with the surrounding rock, which can share part of the flow stress. Namely, the thickness of the penstock can reduce according to the pressure proportion shared by different categories surrounding rock. However, no clear conclusion is obtained for the shared pressure proportion of surrounding rock. The conservative experience value is used in design stage at present [15]. Further study is also required to solve the problem.

6. Conclusions and prospects

Pumped storage power station is of great significance for improving the power supply quality, optimizing the power structure, promoting massive grid-connection of wind power, solar and other renewable energy and realizing the sustainable development of the electric energy. It is likely to develop in the following directions in the future.

(1) The construction scale continues to expand.

With the clean and intelligent energy development policy and the global energy internet construction requirement, the important role of pumped storage power in grid will become increasingly prominent. It is an effective way to plan the large capacity and high parameter pumped storage power station to ensure the power grid safety and improve the electric system regulation and transmission abilities.

(2) PSP application technology keeps innovating.

As the pumped storage power application technology advances all over the world, the large capacity (400 mw) and high head (500 m) pumped storage technology will get breakthrough in the future. The design, construction and operation of the variable speed pump turbine unit will gradually mature in the world. In addition, with the development of the corrosion resistant technology, seawater pumped storage power plant built near the coastal load center is beneficial to the whole
power system flexible and transmission cost reduction, which is a very competitive development direction in the future.

(3) Promoting the developments of various energy sources.

Under the background of green and sustainable energy development, more and more new energy sources especially the intermittent power like wind and solar energy will access to network, which will bring serious grid stability problem. Pumped storage power is an effective way to adjust the grid frequency and phase due to its quickly response and flexible regulation abilities. The significant progress will be made in utilizing various PSP functions to complement and coordinate various sources in grid to maintain the grid stability and improve the power supply quality.

(4) Capacity configuration will be more flexible.

To maximum coordinate the different voltage grade distributes energy integration, according to the principle of hierarchical optimization configuration, constructing the medium or small capacity pumped storage power station to adjust the local grid or distribution network will also be one of the main development directions in the future.

(5) Coordinating various energy storage ways developments.

At present, China's energy storage industry has a certain gap with the developed countries and still in the primary development stage. Pumped storage is one of the most widely used energy storage technology in power system, the comprehensive utilization efficiency is 70% ~ 85%. In the future, pumped storage, chemical battery, flywheel energy storage, energy storage capacitor and other energy storage device will develop in coordinating and complementing to realize the intelligent and clean development aim of power system.

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