Development Situation and Relevant Inspiration of Pumped Storage Power Station in the world

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Abstract. In many countries, pumped storage power stations have gradually become management tools for the power system and are used to meet peak-shaving, valley filling and emergency reserve purpose. In addition, pumped storage power stations can be taken advantage of the unique valley filling function to facilitate the development of wind power, such as in Germany, one of the main approaches to digesting and saving wind power is to maintain a high share of pumped storage power generating capacity. Main factors affecting the scale and share of pumped storage power generating capacity include level of economic development, regional load characteristics, power mix and the peak-shaving capacity of interconnected systems. The capacity of pumped storage power stations is also affected by construction conditions, cost and the economics of other peak-shaving approaches of the power system. In China, the construction of pumped storage power stations is entering a fast-growth period. The government should incorporate the construction of pumped storage power stations into its long and medium-term power development plans and regard pumped storage power stations as part of regional power system. In addition, all of the functions offered by pumped storage power stations should be compensated by ancillary services supporting schemes.

1. Introduction
The first pumped storage power station (PSPS) in the world was set up in 1882 in Zurich, Switzerland. But until the 1950s, the development of PSPS was still very slow that mainly concentrated in a few countries in Western Europe. Starting in the 1950s, the development of PSPS entered to the early stage. New installed capacity is about $3 \times 10^4$ kW per year and until 1960, the installed capacity of PSPS had reached $350 \times 10^4$ kW, occupying 0.62% of the total installed generation capacity. Since the 1960s, PSPS has been rapidly developing and until 1990, the installed capacity had reached $8300 \times 10^4$ kW, occupying 3.15% of the total installed generation capacity. By comparison, the installed capacity of PSPS has increased 23 times in the past 30 years [1-3]. In 2018, the pumped storage capacity in the world was about $13500 \times 10^4$ kW and it would keep rapid growth. According to the forecasting of China academy, global pumped storage capacity would reach $18800 \times 10^4$ kW in 2025.

As a special power supply form, PSPS is not only used to shave peak and fill valley and optimize all kinds of power working position in the system, but also undertake emergency reserve, frequency modulation, phase shifting, black start-up and so on. PSPS can improve the quality of power supply, guarantee the safety of the power supply, and reduce outage time. It’s the important means to solve the problem of power peak shaving, ensure the economic and safety operation of power grid that building the pumped storage power stations with reasonable scales.

This article summarizes the development situation and annual utilization hours of PSPS in typical
nations and analyzes the effect and function of PSPS in different electric systems. The main factors that influence the configuration scale of PSPS in power system are also analyzed to provide reference for improving the development of PSPS.

2. Development Situation of Pumped Storage Power Station

Nowadays, Japan has the largest installed capacity of PSPS in the world. By 2018, Japan has built 45 PSPS including 7 stations with million kilowatt with installed capacity 2537×10^4kW, occupying 11.13% of the total generation capacity of the power system. The capacity shares of PSPS in South Korea, Spain, France, Germany and Italy are also higher than 5%. The capacity share of PSPS in America is only 2.2%, but the total capacity of PSPS has reached the leading level of the world. The total capacity and annual utilization hours of PSPS in major countries are shown in table 1.

The annual utilization hours of PSPS in different countries focus on 400-1000 hours. In America, Britain and Germany, the hours are more than 1000 hours but in Japan and Australia, the hours are under 400 hours especially in Australia, its annual hours is only 67 hours.

Table 1. The installed capacity of PSPP China in 2018

| Countries  | Installed Capacity/10^4kW | capacity shares/% | Annual utilization hours /h |
|-----------|--------------------------|-------------------|----------------------------|
| England   | 274                      | 3.2               | 1168                       |
| America   | 2220                     | 2.2               | 1068                       |
| Germany   | 678                      | 4.65              | 1018                       |
| Sweden    | 11                       | 0.31              | 909                        |
| France    | 699                      | 5.96              | 744                        |
| Korea     | 390                      | 4.93              | 718                        |
| Spain     | 535                      | 5.26              | 598                        |
| Canada    | 18                       | 0.14              | 556                        |
| Italy     | 754                      | 7.52              | 438                        |
| Poland    | 141                      | 4.47              | 426                        |
| Japan     | 2537                     | 11.13             | 335                        |
| Norway    | 129                      | 4.45              | 310                        |
| Australia | 149                      | 2.64              | 67                         |

3. Development trend of PSPS in typical regions

3.1. Areas with resources shortage

In Japan, extreme shortage and high external dependency of energy resources has caused that 80% of fossil energy resource depends on import. Because of the accident of Fukushima nuclear power station, the development of nuclear power has been limited in many ways and the energy problem is increasingly prominent. Japan plans to break the technology and economy barriers that the practical application of renewable energy will face with to develop wind power and solar energy so that the proportion of renewable energy power generation can increase to 20% in 2020. Because of the higher share of installed capacity, in Japan, pumped storage power plant is not only used for shaving peak and filling valley and offering electric power, but also became a management tool to accomplish some functions including frequency modulation, phase shifting, load-following and contingency reserve. At the same time it can improve the quality of power supply and maintain the safe and stable operation of
the system.

In Korea, energy self-sufficient rate is only 3% and energy mainly depends on import. Only Han river can offer water resources for the development and utilization. It stabilized power supply by adjusting the generation facilities proportion between basic load, and peak load. At the end of 2018, there are 6 pumped storage power stations with the installed capacity of 390×10^4kW. Nowadays, Korea has the pumped storage power stations used in peak shaving, valley filling, emergency standby purposes and raising the efficiency of the power grid[4].

3.2. Area with rapid development of new energy
Since 2000, in Spain, the new energy power installed develops rapidly and the installed proportion increases drastically. From 2000 to 2010, installed capacity of wind power increased 1855×10^4kW, and the scale in power system has increased from 4.5% to 20.4%. Solar energy jumped from 1×10^4kW to 460×10^4kW, and the installed proportion increased from less than 0.1% to 4.5%. At the same time, oil-fired generation units for the peak load regulation has the same rapid increasing with wind power that increases the reserve genration capacity, and the ratio between generation reserve capacity and the maximum power load is as high as 2.2. Thus, Spain has a large number of the flexible adjustable generation units in the grid. peak-load adjustment capacity is no long the main factor that limits the development of wind power. The development potential of pumped storage power station has been squeezed, while the increased installed capacity is only 6×10^4kW from 2008 to 2018. But when the total wind power output over the need of load in low period, wind power has to be limited which happened continually in Spain. The unique function of valley filling of pumped storage power station has been an important guarantee to progress wind power and void wind power brownouts in Spain.

Germany has rich coal resources that its coal-fired power generation is account for 50%. The wind power installed capacity is always stay at the front of the world and its proportion is about 18% of the power system. In 2010, the installed capacity of pumped storage power station is 420×10^4kW, from than on, the new pumped storage generation units have been put into operation every year. Germany has 31 pumped storage power stations and the installed capacity has reached 678×10^4kW until 2015. Due to the low proportion of hydroelectric installed capacity, the main measure to expend most wind power is deploying higher proportion of pumped storage power plant and conecting the power grid with neighbor countries. The balance problem about Peak-shaving capacity can be solved in Germany. Therefore, pumped storage power plant in Germany has not only high installed proportion, but also high annual hours of power utilization[5].

3.3. Area with high installed capacity of thermal power or nuclear power
At present, France is the biggest country of nuclear power installed capacity in the world. At the end of 2018, French installed capacity of nuclear power reached 6400×10^4kW, it accounted about 54% of the total capacity, and in the whole year, its generated electricity is 4286×10^4kWh accounted nearly 75%. France has built 18 pumped storage power plants with capacity nomore than 10MW and have different kinds of unit capacity and characteristic which were constructed and managed uniformly by Electric DE France(EDF). The pumped storage power plants are without independent management that it pumps and generates electricity as scheduling requirement of EDF. Pumped storage power plant is used on peak shaving and valley filling and standby application. In addition, 10% of the total capacity is used for frequency adjustment and electricity exchange with other countries. The function of phase modulation is accounted about 12% to 20% of total operation time.

America is the largest energy producer, consumer and importer with rich energy in the world. By the end of 2018, American installed capacity of thermal power has reached 76443×10^4kW, accounted for 76% of total capacity, and the annual amount of generated electricity of thermal power plants has reached 31336×10^4kWh, accounted for 72%. Since 2010, new installed capacity is almost from natural gas power generation and others kinds of power plants remain unchanged in America. At present, America has 20 pumped storage power plants with the capacity more than 20×10^4kW, and the annual hours of power utilization is about 1000 hours. But the annual hours of power utilization in different
states are great different and the most is about 1953 hours, with the task of peak shaving and filling valley and promote rational power system economic operation in the system. Half of the states has annual hours of power utilization less than 1000 hours, the minimum is only 34 hours. Pumped storage power plants in these stations are used for peak shaving, frequency adjustment, phase shifting, improving voltage stability and power supply quality and emergency reserve. In America, most of pumped storage power plants have more than 6 times of operation situation transformation everyday. It’s active in power system and gives full play to its dynamic benefit.

4. Analyse scale allocation influencing factors of pumped storage power plants

Through the analysis the development situation of pumped storage power station in the world, the main factors that influence its scale allocation in the power system include technology and economy. Technical level means the system requirement of peak-shaving capacity. Factors affecting the proportion of pumped storage plants include zone recombination characteristic, power resources structure, peak tuning for interconnected systems, new energy scale and pumping power from grid. In economic level, the economy of construction condition, costing and other peak shaving means influence construction and implementation of pumped storage power plants.

1. In different parts, the economic development level and the structure of power resources determines the load demand of the system and it’s the main factor influences reasonable allocation of pumped storage power plants. Different requirements are put forward for system power quality by the regional economic development level, power quality requirements of developed areas are usually higher than less developed areas. For developed countries, pumped storage power plants are asked urgently because of the important role improving the system of power quality. And considering about the development of pumped-storage power station construction in the developed countries is longer, many factors have led that installed proportion is generally more than developing countries in the world. Especially, in the developed countries such as Japan, Italy, Spain and Germany, the installed proportion is nearly 5% even more. But in developing countries, it’s not any pumped storage power stations yet, for example India, Brazil and South Africa.

2. The power resources structure is one of the decisive factors of capability of the power system. The peak shaving capacity of the system depends on the characteristic of the generation units. Most countries with high proportion of nuclear power has high proportion of pumped storage power plants installed, such as France, Japan, Korea, Germany has more than 15% of nuclear power installed proportion, and their installed proportion of pumped storage power is high. The countries with high conventional hydro power proportion always are less likely to configuration of pumped storage power station, just like Brazil, Canada, Sweden, Finland, Russia and India which has hydro power proportion more than 20%, there are mostly not any pumped storage power stations. Developed countries attach great importance to the reasonable structure of power supply to keep the best proportion of basic load, medium load and peak load, the peak power accounted for 25% to 35% of total installed capacity.

3. Load support capability of area interconnected system influence local construction scale of pumped storage power station. For the non-independent power systems, it can reduce the pressure of local power grid peak shaving and the load power supply demand of pumped storage power stations when the power load performance is good in the interconnected system outside. In Denmark, for instance, wind power installed capacity is up to 29% of the total installed capacity. It needs to support load power supply with a certain size to adapt to the increasing scale and capacity of wind power. Denmark contact to Nordic powerful networks that it can shave peak by hydroelectric power in northern Norway, thus, in Denmark, there has no any pumped storage power plants, but improve the utilization ratio of wind power by regional interconnection system to ensure the safe and stable operation of the grid.

4. The construction term of pumped storage power plants is the main factor influencing the grid scale. The geographical condition requirements is higher in pumped storage power station construction, most of elements are considered including geographical location, terrain conditions, geological conditions, water conditions and environmental implication. Whatever the pumped storage power
5. Other load economy means in the system will directly affect the construction scale of pumped-storage power station. Pumped storage power stations can replace a certain capacity of coal-fired units and benefit the capacity. If the unit investment and annual running cost is lower than thermal power plants alternating peak shaving, investors tend to build more pumped storage power stations and less peaking-shaving thermal power plants. Otherwise, investors will consider more other ancillary services that pumped storage power station can provide but the capacity substitution benefit is greatly reduced.

Besides technical factors and economic factors, policy system factors such as national macro policy, the system construction of pumped-storage power station and electricity price mechanism also influence the long-term development of and enterprise investment enthusiasm even deciding the development and construction scale.

5. The development revelation of pumped storage power station in China
China has a vast territory and it has biggest difference of economic development level, power resource structure and load characteristic each region. By the site condition and characteristic of regional power grid, the construction of pumped-storage power station should be allocated uniformly and be into the power long-term development plan with grid, conventional energy and new energy to realize the optimum benefit of system selection.

In the long run, the functions of the peak shaving, frequency adjustment, phase shifting and system reserve should be taken into the auxiliary services category, that not only guaranteeing reasonable pay-off of pumped-storage power station, but also can enter the ancillary services market step by step and giving full play to the role of the market optimizing the allocation of resources. In addition, it can Reasonably guide the planning and investment, promoting the optimal of power system resources by the price sign from the market.

6. Conclusion
The development of pumped storage power station has a history of 130 years. Operation experience in the world shows that pumped storage power station has good static and dynamic benefit, and it’s the effective and indispensable regulation tool of modern power system. Configuration scale of pumped storage power plant is closely related not only to regional economic development and load structure, but also to power resources structure and peak tuning support capability of interconnected systems. In addition, the economy of construction term, costs and other peak shaving means in the power system influence the implementation of pumped storage power plants.

At present, China is moving to the rapid development stage of pumped-storage plant and should consider the influence factors of scale configuration of pumped-storage power station. It is also necessary to learn from other countries’ operation experience, define the function orientation of pumped storage power plant during different periods and arrange construction scale and time series reasonably.

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