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Study on market mechanisms for participation of small-scale hydropower clusters in electricity energy and ancillary services

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Abstract: The problem of large-scale distributed new energy consumption is highlighted under the double carbon target. Based on the existing distributed small hydropower and local hydrological and geographical conditions, the pumping-storage linkage function of distributed small hydropower can be realized through small-scale transformation according to local conditions, which can significantly reduce the construction cost and improve the profitability of the power station. The development of small hydropower to pumped storage can effectively enhance the flexible regulation capacity of the power grid. Based on an analysis of the investment environment, profitability and option characteristics of small hydropower to pumped storage projects, this paper conducts a study on the operational mechanism of hydropower participation in the electricity energy market and auxiliary services market to provide support for small hydropower to pumped storage investments in the new situation.

1. Introduction

In September 2020, General Secretary Xi Jinping announced to the world at the World Climate Summit China's "double carbon" target: China will strive to peak its carbon emissions by 2030 and work towards achieving carbon neutrality by 2060. In the 14th Five-Year Plan proposal adopted by the Fifth Plenary Session of the 14th CPC Central Committee and the key tasks for 2021 set out at the Central Economic Work Conference, there are also clear plans and requirements for the work related to carbon peaking and carbon neutrality. Whether the "double carbon" target can be achieved on schedule, the transformation of the energy structure is crucial. As the most mature large-scale energy storage technology, pumped storage plants will play a more important role in ensuring the large-scale development of wind power and other clean energy sources and the safe and economic operation of power grids. Figure 1 illustrates the energy conversion for pumped storage power plants.

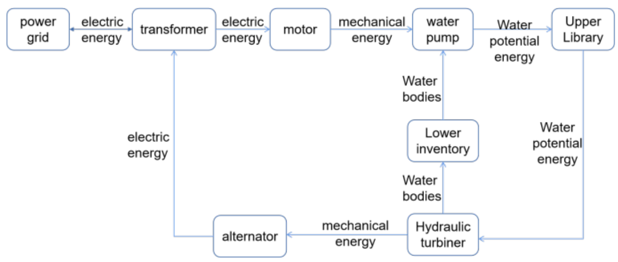

Figure 1 Brief schematic diagram of energy conversion for pumped storage power plants

Pumped storage power plants are a special power source with fast start-up, flexible operation and multiple functions such as energy storage, peak and valley regulation, frequency regulation, phase regulation, standby and black start. The literature [1-3] investigates how pumped storage power plants can be used to assist conventional units to participate in power system peaking. Literature [4-8] provides detailed analysis and research on the role and value of pumped storage power stations in the power system, including their impact on system stability and their participation in market competition. Reference [9] used probability method to calculate the expected annual power shortage in the power system, and used equivalent substitution method to study the division and benefit calculation of the installed capacity of pumped storage power stations between peak shaving, valley filling, frequency regulation, and backup tasks. Reference [10] starts from the power system , The random

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production simulation method was applied to calculate the coal saving and reliability improvement benefits of pumped storage power stations, and the reasonable proportion of pumped storage power stations in the power system was analyzed and studied.With the increasing penetration of renewable energy sources, especially the access to volatile renewable energy sources such as solar and wind power, the role played by pumped storage units in the power system has become increasingly prominent. The construction of pumped storage power stations on a reasonable scale is a necessary means and basic support for solving the problem of peaking in power grids, ensuring the safe and stable operation of power grids, and promoting the economic operation of various power sources.

As a special form of power supply, the positioning and management of pumped storage power stations in the grid is not consistent from country to country, and the specific operation is based on the respective power supply structures and grid conditions, as well as the degree of perfection of the electricity market to adopt the appropriate model.

2. Analysis of the characteristics of small hydropower plants involved in peaking

From the perspective of power system operation, the working principle of pumped storage power stations determines their natural double-peak regulation characteristics, which can effectively reduce the peak-to-valley difference in system load. On the one hand, pumped storage power stations can convert low valley power or system redundancy into potential energy for storage; on the other hand, they can also be used as a power source to release reservoir water for power generation during peak hours. The pumped storage power station can give full play to the peak and valley reduction function, which can improve the capacity margin of the power system, reduce the probability of load shedding in the system due to individual unit failure, ensure the safe and stable operation of the power system, and improve the quality and reliability of power supply.

From the perspective of power system economy, when a high proportion of new energy is connected to the power system, its output uncertainty and load volatility will produce stronger volatility in the power system. To ensure the safe and stable operation of the power system, the power dispatch centre will arrange for peaking units to provide peaking auxiliary services. In China's current power supply structure, thermal power units are the main units responsible for peaking auxiliary services. However, the economics of peaking in thermal power plants are poor, as they operate at high output or start/stop, leading to increased operating costs for the power system. The participation of pumped storage power stations in peaking can relieve the peaking pressure on thermal units, effectively improve the operating conditions of thermal units and enhance the operating economics of the power system.

From the perspective of new energy consumption, wind power and photovoltaic as the representative of new energy generation is affected by the climate, and its uncertainty, volatility and intermittency of power generation put forward higher requirements for system flexibility. At the present stage, China's power supply structure has limited flexible resources and the power system is not sufficiently regulated, which leads to a lack of space for scenery consumption. Pumped storage power stations, with their fast start-stop characteristics, can significantly enhance the regulation capacity of the power system and improve system flexibility. At the same time, pumped storage power stations can make use of abandoned wind and solar energy for pumped storage and promote the consumption of new energy.

3. Analysis of the market participation model for electricity from small hydropower

Since the introduction of the Opinions on Further Deepening the Reform of the Electricity System, China's new round of electricity market reform has achieved remarkable results, with the construction of medium and long-term markets, spot markets and ancillary services markets promoting the formation of a diversified and competitive electricity market pattern. As China's electricity market reform continues to advance, the electricity market and ancillary services market are gradually separated, and the competitive electricity market with balancing mechanisms more fully reflects market supply and demand, using "price signals" to guide pumped storage power plants to "pump low and generate high", thereby addressing the issue of power system regulation. "This will in turn solve the problem of peaking in the power system. At the same time, a pricing mechanism for the provision of peaking services by pumped storage power stations in competitive electricity markets has been developed, allowing pumped storage power stations to earn a reasonable return through peak-to-valley arbitrage. However, in a market environment, pumped storage power stations face a 'role transition' when they participate as independent entities in both the 'regulated load' and 'generation enterprise' roles. In this market environment, however, pumped storage power stations are faced with a "role change", when they participate in the competitive market as both "regulated load" and "power producer".

As large energy storage facilities, pumped storage power stations can participate in the electricity market as independent entities in the dual role of "regulated load" and "generation enterprise". In recognition of their role as market participants, pumped storage power stations can participate in the electricity market independently or form a consortium of interests with other players in the power system. Depending on the mode of dispatch of pumped storage power stations, their participation in the electricity market can be divided into independent and joint modes of operation.

3.1 Independent operation

The independent operation model means that pumped storage power stations compete in the electricity market as independent market players. The independently operated pumped storage plant competes in the electricity market with the objective of maximising its own economic efficiency, arranging its pumping and generation periods and capacity according to market clearances and dispatch results. Under the independent mode of operation, the pumped storage power station derives its revenue from the sale of electricity in the electricity market and bears the operational risks associated with changes in the market and fluctuations in electricity prices. Table 1 shows the details of the Independent Operation Modes.

Table 1 Independent Operation Modes

Electricity price mechanism	**Adoption conditions**	**Advantages**	**Disadvantages**	**Remarks**
Participate in market bidding	The power generation side has achieved marketization and formed a mature auxiliary service market based on bidding.	You can develop your own production plan, fully mobilize the enthusiasm of the power station, and make it play the maximum role in the power grid.	Establishing a sound market mechanism takes a long time.	Used in the California region of the United States
Fixed income + variable income				Domestic use in the UK

3.2 Joint operations

The joint operation mode refers to pumped storage power plants forming a consortium or joint system with other power generation enterprises to participate in the competitive electricity market, such as wind-pumping, wind-light-pumping and fire-wind-pumping joint systems. In the joint system model, a consortium of pumped storage power plants and other power generation enterprises participate in the electricity system to compete, with pumped storage power generation supplementing when other units cannot meet the winning power tenders; and pumped storage pumping consuming the redundant power when there is redundancy in the power of other units, reducing the cost of deviation penalties for the consortium. Within the combined system, pumped storage power stations obtain peaking revenue in a way that distributes benefits in a reasonable manner

3.3 Trading patterns of pumped storage plants in the electricity energy market

In the competitive electricity market involving pumped storage power stations, market players include, in addition to pumped storage power stations, other types of power generation enterprises, electricity sales companies, grid enterprises, electricity consumers, as well as power dispatch and power trading institutions. The electricity market is conducted in the form of full power declaration and centralised optimisation. With the exception of units that are prioritised for dispatch according to policy requirements, all other generating units will declare their power and prices at short-term marginal costs, and will be dispatched by the power trading institutions and dispatch centres in descending order of price.

Under the energy market trading mechanism designed in this paper, pumped storage plants have a distinctive "producer-consumer" character. On the one hand, when competing in the market as 'generators', they trade strategically with the objective of minimising operating costs; on the other hand, when competing in the market as 'consumers' (in the pumped operation phase), they trade strategically as 'price takers' on the consumer side. On the other hand, when competing in the market as a "power user" (pumped operation phase), it trades strategically as a "price taker" on the customer side. At the same time, other generating companies will trade strategically with the objective of minimising their operating costs. The trading centre will complete the day-ahead electricity market clearing based on the offer information received during the specified time periods, and obtain the day-ahead electricity price for each time period on the operating day as well as the winning bids from each market player. Pumped storage power plants will arrange the charging and discharging power for each period of the operating day based on the clearing of the trading market.

4. Analysis of the market participation model for ancillary services for small hydropower

4.1 Participation in the spot market ancillary services trading model

As the institutional mechanism of the ancillary services market is not yet sound [11] and there are a wide range of ancillary services [12], the way in which pumped storage power stations participate in the ancillary services market is designed to be traded, taking frequency regulation as an example. Pumped storage power plants participate in the FM market and will become benchmark units due to their relatively better FM performance. When a pumped storage power station participates in the FM market as a single generation unit, the FM declaration includes the FM capacity, the FM capacity price and the FM mileage price. The FM revenue is based on the sum of the FM capacity charge and the FM mileage charge in the ancillary services market to obtain the total FM charge. The pumped power expenditure is settled at the load centre price, in accordance with the principle of "day-ahead benchmark, real-time differential, contractual differential", overlaid with the relevant transmission and distribution price for settlement.

As shown in Figure 2, a pumped storage plant can win a bid in the FM market and receive the corresponding FM capacity and FM mileage costs by providing FM services. The FM capacity and FM mileage costs are calculated on a daily basis and settled on a monthly basis, with the monthly FM capacity costs and FM mileage costs calculated as follows:

$$S_{bc}=\sum_{i=1}^{n}(K_{b,i}Q_{bc,i}\pi_{bc,i})$$

$$S_{bm}=\sum_{i=1}^{n}(K_{b,i}Q_{bm,i}\pi_{bm,i})$$

where: n is the total number of trading periods in the monthly spot market. $K_{b,i}$ is the average of the historical frequency regulation performance indicators of the generating unit in the i-th trading period. $Q_{bc,i}$ is the winning FM capacity of the generating unit in the i-th trading period. $Q_{bm,i}$ is the actual FM mileage of the generating unit in the i-th trading period. $\pi_{bc,i}$ is the FM capacity settlement price for the i-th trading cycle. $\pi_{bm,i}$ is the FM mileage settlement price for the i-th trading cycle.

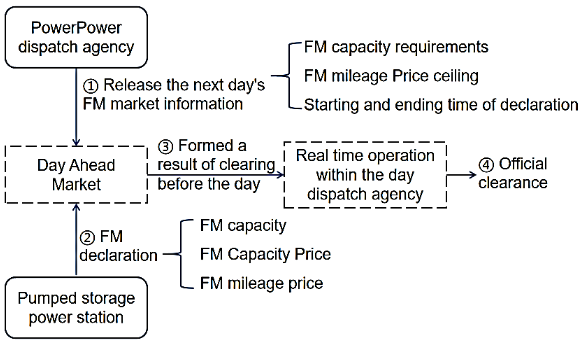

Fig. 2 Ancillary services market for pumped storage power stations FM trading approach

5. Summary

Pumped storage power plants are a special power source with fast start-up and flexible operation. With the increasing penetration of renewable energy sources, especially the access to fluctuating renewable energy sources such as solar and wind power, the role played by pumped storage units in the power system has become increasingly prominent. The construction of pumped storage power stations of a reasonable scale is a necessary means and basic support for solving the problem of grid peaking, ensuring the safe and stable operation of the grid and promoting the economic operation of all types of power sources. The next step is to establish a reasonable market access mechanism to encourage and support pumped storage in the auxiliary services market to provide peak regulation, frequency regulation, standby and black start services; establish a series of performance evaluation indicators to assess the capacity value of pumped storage tariffs; suggest improving the auxiliary services price mechanism, allowing pumped storage power stations to participate in auxiliary services transactions jointly with units or as independent entities, and promoting the entry of pumped storage power stations into the Ancillary services market.

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