Model construction of pumped storage to promote wind-photovoltaic consumption considering uncertainty of wind-photovoltaic output

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Abstract. With the continuous development of renewable energy in China, to improve its competitiveness in the power market, this paper considers the participation of pumped storage power plants in renewable energy generation system on the basis of wind-photovoltaic complementary joint dispatching, and then proposes a wind-photovoltaic-pumped storage joint dispatching optimization method considering the uncertainty of wind and solar output. This method takes the minimum wind and solar curtailment as the goal, considers the operation constraints of wind-photovoltaic generating units and pumped storage generating units, and establishes a coordinated dispatching model, which provides the basis and theoretical basis for formulating the output scheme of the coordinated dispatching of wind, photovoltaic and pumped storage.

1. Introduction
In recent years, the energy crisis and environmental problems have become the focus of the world, making the renewable energy mainly composed of wind power and photovoltaic widely used. High proportion of renewable energy has become an inevitable choice for the development of energy and electricity. By the end of 2019, the grid-connected wind power and PV power were 210 GW and 205 GW, respectively, and the total installed capacity of full-aperture power generation reached 20.6 %, which was the main force of China’s energy structure.

In the future, renewable energy will continue to grow and will gradually become the main form of energy supply. Wind power and photovoltaic power generation have significant randomness and volatility. Large-scale direct grid connection will have a great impact on the safe and stable operation of the power grid. The future power system needs more flexible peak shaving and energy storage characteristics.

Pumped storage power plant mainly undertakes a variety of functions in the power system, such as peak shaving and valley filling, frequency modulation and phase modulation, accident standby, black start and so on. It has the characteristics of flexible operation, clean and efficient, and better economy. By the end of 2019, the installed capacity of pumped storage power plants in China was 30.29 GW, ranking first in the world. With the development of high proportion of renewable energy, the functional orientation of some pumped storage power plants has gradually expanded to photovoltaic, wind power
and other intermittent energy sources. Through multi-energy complementary ways, high-quality power output and utilization are realized.

This paper considers the participation of pumped storage power plants in renewable energy generation system on the basis of wind-photovoltaic complementary joint dispatching, and then proposes a wind-photovoltaic-pumped storage joint dispatching optimization method considering the uncertainty of wind and solar output.

2. Optimization theory of joint dispatching of wind-photovoltaic-pumped storage
The marginal cost of wind power generation and photovoltaic power generation is lower than that of conventional generators, but it is obviously affected by weather, with significant randomness, volatility and intermittent characteristics. Independent wind or photovoltaic power generation systems cannot provide stable and reliable output power, which greatly weakens the competitiveness of renewable energy in the power market. But wind power and photovoltaic power have very good complementary performance. For the power generation enterprises with wind farms and photovoltaic power plants at the same time, if the interconnection is realized in the geographical position, the wind and photovoltaic power generation can be combined to form a wind-photovoltaic complementary combined power generation system, which can alleviate the influence of output fluctuation to a certain extent and improve the power penetration of renewable energy to the grid. However, it is difficult to improve the competitiveness of renewable energy in the power market only by the complementary advantages of wind and solar energy. The main reasons are as follows: 1) It is difficult to eliminate the output deviation caused by the prediction error of wind power and photovoltaic. 2) The generation power after wind-photovoltaic combination is generally inconsistent with the electricity price trend of the power market, and the income of the power generation enterprises has a large room for improvement. Therefore, it is necessary to combine energy storage equipment to adjust the balance.

Pumped storage power plant is an energy storage facility with large capacity and mature technology in power system. It is generally considered that only construction cost and operation and maintenance cost can be ignored. In recent years, the related technologies of pumped storage power plants have developed rapidly in China and the world. The operation of pumped storage power plant combined with wind power and photovoltaic power generation can adjust the output plan of the system to conform to the trend of electricity price, reduce wind abandonment and increase power generation income. On the other hand, it can balance the output deviation caused by wind and PV power prediction error and reduce economic penalties. The operation of wind power and photovoltaic power generation combined with pumped storage power plant can effectively improve the competitiveness of renewable energy generation in the electricity market. In this paper, on the basis of considering the complementary characteristics of wind and solar, the pumped storage power plant is used to cooperate with the operation and regulation of wind farm and photovoltaic power plant to form a combined operation power generation system.

3. Joint dispatching principle of wind-photovoltaic-pumped storage

3.1. Dispatching principle of renewable energy generation
With the rise of distributed renewable energy generation technology, the dispatching problem of wind power and photovoltaic power generation has gradually become an important problem in the safe and stable operation of power system. With the progress of renewable energy output prediction technology, wind farms and photovoltaic power plants should be able to make prediction systems to institutions, including the prediction of ultra-short-term power, the prediction of short-term wind power and photovoltaic power, and the prediction of load, so as to facilitate the periodic power distribution plan, so as to issue the power generation plan curves of wind farms and photovoltaic power plants and the power generation plan curves of conventional power plants, and confirm the three or two parties of wind farms and photovoltaic power plants and thermal power plants. Renewable energy power dispatching principle is to ensure the stability and safety of the power grid under the premise of combining load
forecasting, wind power output forecasting, photovoltaic output forecasting, security constraints and other factors, a comprehensive consideration of the errors in the system, power generation dispatching plan, so that as much as possible into the grid.

3.2. Joint dispatching principle of wind-photovoltaic-pumped storage

The principle of wind-photovoltaic-pumping storage joint dispatching under the unified dispatching of power grid can be summarized as follows. Without affecting the power quality and safety and stability of power grid, pumped storage power plant needs to give full play to its dynamic and static benefits based on the wind-photovoltaic output and the overall characteristics of the wind-photovoltaic-pumping storage system, so as to maximize the use of wind power and photovoltaic resources, alleviate the phenomenon of abandoning wind and solar, reduce the use of non-renewable energy, and improve the overall efficiency of the system.

4. Construction of joint dispatching system of wind-photovoltaic-pumped storage

This paper mainly considers the synergy between wind-photovoltaic power generation system and pumped storage power plant, and constructs a joint dispatching system of wind-photovoltaic-pumped storage as shown in Figure 1. The main operating modes of the system are:

1. All renewable energy power is supplied to pumped power plants. ① closed, ② disconnected, at this time all renewable energy power will be supplied to the pumping plant. ③ closed. If the power supply is greater than the load demand, on the basis of the pumped storage power plant meeting the load demand, the remaining electricity can be provided to the pumping unit through closed ④ for pumping.

2. Some renewable energy power supply pumped storage power plant. ③ closed, and all loads are satisfied by the pumped storage power plant. ④ closed, when the load level is low, the renewable energy power supplies the remaining power to the pumping unit after meeting the load demand. ② closed, when the wind and light output does not exceed the upper limit of acceptable renewable energy power, all renewable energy power is directly input into the grid to meet the demand; When the wind and light output exceeds the upper limit of the renewable energy power, on the basis of the above operation, it is necessary to close ① and use the excess part of the renewable energy power for pumping.

3. All renewable energy power is directly input into the grid. If ② is closed and ① is disconnected at the same time, all renewable energy generation will be directly fed into the grid to meet load requirements. ③ closed, pumped storage power plant is used for phase modulation, frequency modulation operation and meeting the load. ④ closed, When the load level is low, after the power generation side meets the load demand, the remaining energy is provided to the pumping unit. In this mode, the pumped storage power plant unit adopts the operation mode of phase modulation and frequency modulation, which makes all renewable energy power input into the grid, and ensures that voltage and frequency fluctuations will not occur when inputting large proportion of renewable energy power.
5. Joint dispatching optimization model of wind-photovoltaic-pumped storage

The model mainly considers three parts of wind power generation system, photovoltaic power generation system and pumped storage system. On the basis of the wind-photovoltaic-pumping and storage joint dispatching system established in the third section, through the operation of each equipment of the system, combined with the relevant constraints of the equipment itself and the coordinated operation of the system, the internal members are optimized and combined to formulate the output plan of each equipment, which provides the basis and theoretical basis for the formulation of the system output plan.

5.1. Objective function

In this paper, considering the peak shaving and valley filling effect of pumped storage, the curve of stabilizing wind and wind and solar output fluctuation is divided into 24 periods per day. The objective function is to minimize the amount of abandoned wind and solar energy in the region. The objective function is as follows:

$$\text{min} \left( P_{w,t} + P_{pv,t} \right) = P_{w,t} + P_{pv,t} - P_{ps,t} - P_{a,t}$$ (1)

Where, $P_{w,t}$ is abandon wind power; $P_{pv,t}$ is abandon PV power; $P_{w,t}$ is power generation of wind turbines; $P_{pv,t}$ is power generation of photovoltaic power generators; $P_{ps,t}$ is pumping power of a pumped storage power plant; $P_{pv,t}$ is power generation of pumped storage power plant; $P_{a,t}$ is regional load side electricity load.

5.2. Constraint condition

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5.2.1. Wind power generation system. Wind power is one of the most mature and valuable power generation methods in renewable field. China is rich in wind energy resources. Affected by weather, topography and other environmental factors, the distribution of wind energy resources is uneven. The wind energy resources in the northeast, north, northwest and coastal areas are rich, and the wind energy resources in Yunnan, Guizhou and Gansu are less. Wind power output has strong volatility and uncontrollability. In the four seasons, wind energy resources in autumn are more abundant than the other three seasons, and the daily output is unstable. The output can be varied from 0 to full within an hour. In the wind-photovoltaic-pumping storage unit, the wind power generation constraint is:

\[
\min \leq P_{w,t} \leq \max
\]

(2)

Where, \(P_{w,t}^{\max}\) is nominal power wind power output at time \(t\); \(P_{w,t}^{\min}\) is wind turbines.

5.2.2. Wind power generation system. China has a vast territory and abundant solar radiation resources. Overall, the solar energy resources in the western region are greater than those in the eastern region. Among them, the Qinghai-Tibet Plateau is the most abundant, and the annual total radiation is more than 1800 kWh / m². The resources of Sichuan Basin are relatively low, and there are areas less than 1000 kWh / m². The utilization of solar energy can be divided into solar thermal and photovoltaic. The photovoltaic power generation system with molten salt as heat absorbing medium mainly converts light energy into heat energy and then into electricity. Photovoltaic power generation directly converts light energy into electricity through the photovoltaic effect of solar panels. Compared with photothermal power generation, photovoltaic power generation is less difficult and more widely used. Photovoltaic power generation is mainly composed of volt components, controllers, inverters and other accessories. Its power generation is related to solar intensity and photoelectric conversion efficiency.

\[
P_{pv,t} = AI\eta_{pv}
\]

(3)

Where, \(A\) is Photovoltaic installation capacity; \(I\) is solar intensity; \(\eta_{pv}\) is photoelectric conversion efficiency.

5.2.3. Pumped storage system. At present, pumped storage is the most mature energy storage technology, which is applied to the power supply side. By reasonably controlling the time of pumped storage and water discharge, the peak limit period can be shifted to the valley non-limit period, and the effect of peak clipping and valley filling can be achieved. Pumped storage power plant has upper and lower reservoirs. When storing electricity, the water in the lower reservoir is pumped into the upper reservoir. When generating electricity, discharge the upper reservoir to the lower reservoir.

When the renewable energy output is higher than the local load and the large power grid has no space to accommodate, the pumped storage power plant begins to charge and store energy; When the output level of renewable energy is low or not limited, the pumped storage power plant discharges water to generate electricity, improves the energy utilization efficiency of renewable energy plants, and ensures that the main transformers are not overloaded. Therefore, with the help of pumped storage power plant on the characteristics of energy access, as far as possible to reduce the risk of wind and solar abandonment to a minimum, help to absorb renewable energy.

(1) Power constraint of pumped storage. Pumping and power generation of pumped storage power plant cannot be carried out simultaneously, and there is at most one working state at the same time.

\[
P_{ps,t}^0 P_{ps,t}^1 = 0
\]

(4)

\[
0 \leq P_{ps,t}^1 \leq P_{ps,t}^{1,\max} \times k_1
\]

(5)

\[
P_{ps,t}^0 \times k_0 \leq P_{ps,t}^0 \leq P_{ps,t}^{0,\max} \times k_0
\]

(6)
Where, \( P_{ps,t}^0 \) is working power of pumped storage pumping units, \( P_{ps,t}^1 \) is working power of pumped storage generation units. \( k_t \) is operational number of pumped storage pumping units, \( k_0 \) is operational number of pumped storage power generation units.

(2) Water quantity constraint of pumped storage. Pumping and generating power of pumped storage power plant is related to reservoir capacity, power generation, productive head.

\[
\begin{align*}
V_{up,t} &= V_{up,t-1} + \frac{P_{ps,t}^0 \eta_{ps}^0}{gH_y} - \frac{P_{ps,t}^1}{gH_y \eta_{ps}} \\
V_{dn,t} &= V_{dn,t-1} - \frac{P_{ps,t}^0 \eta_{ps}}{gH_y} + \frac{P_{ps,t}^1}{gH_y \eta_{ps}} \\
V_{dn}^\text{min} &\leq V_{dn,t} \leq V_{dn}^\text{max} \\
V_{up}^\text{min} &\leq V_{up,t} \leq V_{up}^\text{max}
\end{align*}
\]

Where, \( V_{up}^\text{min}, V_{up}^\text{max} \) are the minimum and maximum water storage of the upper reservoir; \( V_{dn}^\text{min}, V_{dn}^\text{max} \) are the minimum and maximum water storage of the lower reservoir; \( V_{dn,t} \) is the water storage of the upper reservoir at time \( t \); \( V_{dn,t} \) is the water storage of the lower reservoir at time \( t \); \( g \) is acceleration of gravity; \( H_c \) is productive head; \( H_y \) is pumping lift; \( \eta_{ps}^0 \) is pumped storage conversion efficiency; \( \eta_{ps}^1 \) is Power generation conversion efficiency.

5.2.4. Power balance. In addition to meeting the power constraints of the above systems, the power in the whole system needs to maintain a balanced state. Some of the power supply at the power supply side meets the electricity load, and some is used for pumped storage. Some that cannot be stored in the pumped storage power plant are abandoned.

\[
P_{pv,t} + P_{w,t} = P_{ps,t}^0 - P_{ps,t}^1 + P_{dz,t} + P_{w,t}^\prime + P_{pv,t}^\prime
\]

6. Conclusion

This paper fully considers the advantages and limitations of wind power and photovoltaic power generation in the application of renewable energy power generation in China, and analyzes the working principle and energy storage characteristics of pumped storage power plant. Subsequently, based on the coordinated dispatching of traditional wind-photovoltaic power generation system, the feasible principle of pumped storage participating in wind-photovoltaic coordinated power generation is proposed, and the wind-photovoltaic-pumped storage joint dispatching system is established. Finally, taking the minimum wind and light curtailment as the goal, the optimization model of wind-photovoltaic-pumped storage joint dispatching is established, which provides a theoretical basis for the formulation of wind-photovoltaic-pumped storage joint dispatching scheme.

Acknowledgements

This work was supported by the National Social Science Fund of China (19ZDA081) and the Fundamental Research Funds for the Central Universities (2020MS067).

References

[1] GAO Jie, A Research on Operation of the Pumped-storage,Photovoltaic and Wind Power Hybrid System, Hydropower and Pumped Storage, 2020,6(05):25-29+37.
[2] SHENG Siqing, SUN Xiaoxia, Operational Optimization Model for Combined Operation of
Wind Power and Pumped-storage Plant, Proceedings of the CSU-EPSA, 2016,28(11):100-103.

[3] MA Shiyi, LI Jiancheng, DUAN Cong, WU Jun, XU Tong, Joint Operation Optimization of Wind-Photovoltaic-Pumped Hydro Storage Based on Electricity Market, Smart Power, 2019,47(08):43-49.

[4] LI Jiarong, LIN Jin, XIAO Jinyu, SONG Yonghua, TENG Yue, Technical and Energy Consumption Comparison of Power-to-Chemicals(P2X) Technologies for Renewable Energy Integration, Journal of Global Energy Interconnection, 2020,3(01):86-96.

[5] LV Wen-jing, WANG Ling-feng, JI Chao-chao, Study on Optimal Operation of Combined System of Wind-Pumped Storage Power, Telecom Power Technology, 2016,33(04):71-73.

[6] ZHU Lingzhi,CHEN Ning,HAN Hualing, Key Problems and Solutions of Wind Power Accommodation, Automation of Electric Power Systems, 2011,35(22):29-34.

[7] XIE Min,KE Shaojia,JI Xiang,CHENG Peijun,LIU Mingbo, Microgrid Dynamic Economic Dispatch Considering Wind-photovoltaic Complementary Characteristics, Smart Power, 2017,45(08):9-14+20.

[8] XIAO Yunpeng,WANG Xifan,WANG Xiuli,BIE Zhaohong, Review on Electricity Market Towards High Proportion of Renewable Energy, Proceedings of the CSEE, 2018,38(03):663-674.

[9] YI Chen,RENI Jianwen,YU Jia, Research on Capacity Optimization of Pumped-Storage Power Plant with Wind Farm, Electric Power, 2018,51(02):99-104+124.

[10] DING Yan, YANG Xiaokun, DENG Changhong, Wind Power Characteristics and its Quantitative Research on Power Generation Peak Shaving, ubei Electric Power,2017,41(12):28-32.