Multi-Objective Optimization Based Joint Dispatch Model of Wind-Solar-Hydro-Thermal Pumped Storage

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Abstract: In this paper, a joint dispatch model of wind-solar-hydro-thermal pumped storage was proposed, taking into account of the basic requirements of minimum system operation cost, minimum load fluctuation and multiple constraints guarantee. Used NSGA-II multi-objective optimization algorithm to solve the problem, so as to verify the feasibility of the model. The model with good adaptability in multi-objective function can optimize the power of pumped-storage units aiming to improving the peak and valley volatility of the net load with pumped storage, and it can optimize the output of thermal power units with the goal of minimizing system operating costs. The pumped-storage effect can be effectively used to relieve the peak load pressure of thermal power units, which can provide a good reference for comprehensively improving the level of renewable energy utilization and increasing comprehensive benefits.

1. Introduction
The increasing contradiction of power system peak regulation has brought a series of problems to power system planning and operation [1]. In this case, pumped-storage power station, as a representative of peak regulation power source, plays a key role in power system peak regulation operation. Under the current background that a complete and orderly planning policy for pumped storage power stations has not yet been formed, how to further guide the benign construction of pumped storage power stations so that it is conducive to the optimized operation of the system without over-construction, is one of the contents that need to be studied in system planning [2]. Moreover, wind power and photovoltaic have the advantages of short construction period and quick effect and have great development prospects. However, as wind turbines do not have the fast peak and frequency modulation capabilities of conventional generators, and wind power produces more power during the low valley at night in most cases while producing less in the daytime peak period (it is a "reverse peak shaving" characteristic of wind power generation), the peak regulating ability of power system after large-scale wind power integration will be seriously weakened [3]. Therefore, the large-scale renewable energy integration system represented by wind and solar power has a great impact on the peak regulating capacity of the power system. The existing grid system cannot meet the requirements of large-scale grid-connected consumption of renewable energy. Constraints have led to serious problems of wind, water and light abandonment in some areas. Therefore, rational planning of wind power and solar grid-connected capacity, and enhancement of grid peak regulating capacity are also related to whether the entire power...
system can better play the role of energy saving and emission reduction, improve the level of renewable energy utilization, and equip the system with more optimal operation [4].

Under the background of large-scale development of wind and solar resources and the need for a large number of system peak regulating capacity, there are a variety of energy storage devices and peak regulating devices [5]. The mature technologies include pumped storage power station, lithium energy storage, sodium energy storage, and flywheel energy storage, etc. Due to the huge power generation capacity of the pumped storage power station and the rapid start-up of the motor, it is still the preferred unit to solve the current peak regulating problem when the conditions are available[6, 7]. Pumped-storage power stations are not affected by incoming water, it is difficult to affect the operation performance of pumped storage power station in wet and dry seasons and reservoir operation mode. Therefore, it is a good peak-regulating power source to promote more renewable energy. Domestic and foreign scholars, literature [3] established a "wind, solar, thermal, pumping, and storage" multi-energy complementary optimization scheduling model, and proposed to use dynamic inertia weight particle swarm optimization algorithm to solve, in order to achieve the optimization goal of minimum total operation cost of the system. Literature [8] established an optimization model for the joint operation of pumped storage units and thermal power units. On this basis, a practical system is taken as an example for joint optimization simulation. Literature [9] established a wind-solar pumped-storage combined power generation system, which was solved by the immune particle swarm algorithm. Literature [10] optimizes the wind-storage combined operation mode with the goal of the lowest operating cost of thermal power and discusses the economic benefits of wind-storage combined operation during heating and non-heating periods. However, the pumping power of pumped storage in this study is set to a fixed value, which is not conducive to giving full play to its regulating ability. In literature, the wind thermal storage system is regarded as a whole, and the confidence level is used to constrain the power of wind thermal storage system. Based on the chance constrained programming theory, the economic scheduling model of wind thermal storage system is constructed, and the influence of confidence level on system cost is analyzed.

However, the above-mentioned literature has less research on the joint optimization operation of high proportion of renewable energy grid-connected utilization of thermal power and pumped storage peak regulation, which is not fully applicable to China's actual current situation and future demand. Relying only on the flexibility of thermal power units for adjustment will inevitably cause frequent starts and stops of thermal power units, threatening the safety and economy of power grid operation. Therefore, the use of energy storage technology is an effective mean to solve the problem of grid dispatching and ensure the stability of the grid, and it has increasingly shown an important role in improving the flexibility of the power system. This paper proposes a multi-objective joint dispatch model for wind-solar-hydro-thermal pumped storage power plants, which takes into account of the minimum system operating cost, minimum load fluctuation, and the basic requirements of multiple constraint guarantees, and provides an analysis method for the joint dispatch of multiple renewable energy sources. It is proposed to reduce the rate of curtailment of renewable energy through the joint operation of renewable energy and traditional power sources and coordinate with energy storage devices to provide a good reference for comprehensively improving the level of renewable energy utilization and improving comprehensive benefits.

2. Scheduling Optimization Modeling Optimal dispatching model of wind-hydro-thermal pumped-storage combined power generation system

2.1 Co-generation optimal dispatch model
The joint dispatch of wind-solar-hydro-thermal pumped-storage power stations is to make full use of the complementary characteristics of multiple sources and encourage each power source to give full play to its role, so as to achieve the goal of improving the clean energy consumption rate and the economic and smoothness of system operation. The model optimizes the power of pumped-storage units with the goal of improving the peak and valley volatility of the net load with pumped storage and
optimizes the output of thermal power units with the goal of minimizing system operating costs. The pumped-storage effect can be effectively used to relieve the peak-regulating pressure of thermal power units.

**Objective function 1:** the minimum of load fluctuation as the goal

\[
E_i = \min \frac{1}{T} \sum_{t=1}^{T} \sum_{k=1}^{K} \left[ \left( P_{net, t}^{i} - P_{bg, k}^{i} + P_{kp, k}^{i} \right) - P_{net, ave} \right]^2
\]

\[
P_{net, t}^{i} = P_{load, t}^{i} - P_{w, t}^{i} - P_{pv, t}^{i} - P_{JL, t}^{i}
\]

\[
P_{net, ave} = \frac{1}{n} \sum_{t=1}^{T} P_{net, t}^{i}
\]

Where: \( T \) is the dispatch period; \( K \) is the number of pumped storage power stations; \( P_{load, t}^{i} \) is the load power at the \( t \) moment; \( P_{net, t}^{i} \) is the net load power at the \( t \) moment; \( P_{net, ave} \) is the average net load power in the dispatch period; \( P_{JL, t}^{i} \) is the Runoff power station output; the calculation step is 15 minutes, and the dispatch period is 1 day.

**Objective function 2:** the goal of minimizing the daily operating cost of the system

To achieve the goal of minimizing the daily operating cost of the system, construct a dispatch method for a multi-energy power system. In this paper, the operating cost of thermal power plant mainly considers the startup cost; the operating cost of pumped storage power plant mainly considers the startup cost of energy storage and power generation.

\[
F = F_G + F_{H2}
\]

Where: \( F \) is the daily operating cost; \( F_G \) is the start-up cost of the thermal power plant in the dispatch period; \( F_{H2} \) is the operation cost of the pumped-storage power plant in the dispatch period.

\[
F_G = \sum_{i=1}^{N_G} \sum_{t=1}^{T} \left\{ f_i \left[ P_{Gi}^{i}(t) \right] \cdot U_i(t) + S_i \cdot [1 - U_i(t-1)] \cdot U_i(t) \right\}
\]

Where: \( f_i \left[ P_{Gi}^{i}(t) \right] \) is the operating cost of thermal power plant \( i \) in \( t \) time; \( T \) is the dispatch period; \( N_G \) is the total number of thermal power plants; \( P_{Gi}^{i}(t) \) is the power for thermal plant \( i \) at time \( t \); \( S_i \) is the starting cost for thermal power plants; \( U_i(t) \), \( U_i(t-1) \) are the starting state or stopping state of thermal power plants at time \( t \) and \( t-1 \), respectively, and \( U_i(t) = 1 \) shows the power-on state, vice versa. \( f_i \left[ P_{Gi}^{i}(t) \right] = \left[ a_i \cdot P_{Gi}^{i}(t)^2 + b_i \cdot P_{Gi}^{i}(t) + c_i \right] \cdot S_{coal}^{i} \)

Where: \( a_i, b_i, c_i \) are the operating cost parameters for the power plant \( i \); \( S_{coal}^{i} \) is the current coal prices.

\[
F_{H2} = \sum_{i=1}^{n_{H2}} \sum_{j=1}^{n_{H2}} \left[ B_{f, i-j} \cdot \left( 1 - B_{f, i-j} \right) \cdot D_{f, i-j}^{H2} + B_{c, i-j} \cdot \left( 1 - B_{c, i-j} \right) \cdot D_{c, i-j}^{H2} \right]
\]

Where: \( n_{H2} \) is the total number of pumped storage power stations, \( D_{f, i-j}^{H2} \) and \( D_{c, i-j}^{H2} \) are the start-up costs of the power generation and energy storage operating states of the pumped storage power station.
2.2 Constraints

1) Power balance constraint

\[
\sum_{i=1}^{n} P_{H,i,t} + \sum_{i=1}^{N} P_{Gi,t} + \sum_{j=1}^{m} \left( P_{j,t}^{bg} - P_{j,t}^{hp} \right) = P_{\text{netload},t}
\]  

(6)

Where: \( j \) stands for the index number of the pumped-storage unit; \( P_{j,t}^{bg} \) denotes the power generation output of the pumped-storage unit \( j \) at the \( t \) moment, \( P_{j,t}^{hp} \) is the pumped water output; \( P_{\text{netload},t} \) signifies the net load size of the time period \( t \).

2) Maximum and minimum output constraints of thermal power units

\[
P_{Gi,\text{min}} \leq P_{Gi,t} \leq P_{Gi,\text{max}}
\]

(7)

In the formula, \( P_{Gi,\text{min}} \) and \( P_{Gi,\text{max}} \) are the minimum and maximum output of the unit, MW

3) Climbing speed constraints of thermal power units

The response speed of the thermal power unit is slow, and the output cannot be changed in time when the load changes fast. The climbing speed is restricted as follows:

\[
D_{Gi}\Delta t \leq P_{Gi,t+1} - P_{Gi,t} \leq U_{Gi}\Delta t
\]

(8)

In the formula, \( D_{Gi} \) and \( U_{Gi} \) are the declining and rising rates of the active power output of the \( i \)-th unit, MW/h; \( \Delta t \) is the duration of time period, h.

4) Hydropower station constraints: water balance constraints, flow balance constraints, reservoir water storage constraints, reservoir water level constraints

\[
\begin{align*}
V_{i,t+1} &= V_{i,t} + (Q_{i,t} - Q_{i,t}^r - Q_{i,t}^q)\Delta t \\
Q_{i,t}^r &= Q_{i,t-\Delta t} + Q_{i,t}^q + q_{i,t} \\
V_{i,t}^{\text{min}} &\leq V_{i,t} \leq V_{i,t}^{\text{max}} \\
Z_{i,t}^{\text{min}} &\leq Z_{i,t} \leq Z_{i,t}^{\text{max}}
\end{align*}
\]

(9)

Where: \( Q_{i,t}^r \) is the inflow flow; \( Q_{i,t} \) stands for the power generation flow; \( Q_{i,t}^q \) refers to the discarded water flow; \( q_{i,t} \) is the interval flow; \( V_{i,t} \) denotes the reservoir storage capacity; \( Z_{i,t} \) means the reservoir water level value; \( V_{i,t}^{\text{min}}, V_{i,t}^{\text{max}} \) are the minimum and maximum values respectively; \( Z_{i,t}^{\text{min}}, Z_{i,t}^{\text{max}} \) are the minimum and maximum values respectively; \( \Delta t \) is the time period for optimizing the unit.

5) Relevant constraints of pumped storage units

(1) Storage capacity constraints of pumped storage power stations

The storage capacity of the reservoir at any time is required to be between the minimum and maximum values, namely:

\[
W_{\text{min}} \leq W_{i,t} \leq W_{\text{max}}
\]

(10)

Where: \( W_{\text{min}}, W_{\text{max}} \) are the upper and lower limits of the reservoir’s energy storage

The pumped storage unit is a daily adjustment method, and the storage capacity of the reservoir is a certain value. The range of changes in the reservoir energy storage at the beginning and the end of the day must be restricted to ensure that the power absorbed by the pumped-storage power station during the daily trough is used for power generation during peak hours. The range of changes is restricted as follows:
\[ \delta_{\text{min}} \leq W_{24} - W_0 \leq \delta_{\text{max}} \]  

Where: \( \delta_{\text{min}}, \delta_{\text{max}} \) are the minimum and maximum dynamic storage capacity at the beginning and end of the day, and the size is 5% of the available storage capacity.

(2) Restriction on the balance of electricity in the reservoir of the pumped storage power station

① When the pumped-storage unit generates electricity, the electricity of the reservoir in the next period is equal to the electricity of the reservoir in the previous period minus electricity generated by the unit;

② When the pumped storage unit pumps water, the power of the reservoir in the next period is equal to the power of the reservoir in the previous period plus electricity absorbed by the unit.

\[ W_{t+1} = W_t - P_{j,t}^g / \eta_g \times 1h + P_{j,t}^p \times \eta_p \times 1h \]  

Where: \( \eta_g \) and \( \eta_p \) are the power generation efficiency and pumping efficiency respectively; \( P_{j,t}^g \) and \( P_{j,t}^p \) are the power generation and pumping power of pumped storage unit \( j \) in time period \( t \) respectively.

(3) Restriction on power generation and pumping output of pumped storage units

\[ P_{\text{min}}^{j} \leq P_{j,t}^g \leq P_{\text{max}}^{j} \]  

\[ P_{\text{min}}^{j} \leq P_{j,t}^p \leq P_{\text{max}}^{j} \]  

In the two formulas, \( P_{\text{min}}^{j} \) and \( P_{\text{max}}^{j} \) are the minimum and maximum power output limits of pumped storage unit \( j \); \( P_{\text{min}}^{j} \) and \( P_{\text{max}}^{j} \) stand for the minimum and maximum pumping output limits; \( x_{j,t}, y_{j,t} \) denote two Boolean variables that indicate the unit’s operating conditions during period \( t \), and 0 means that the unit is shut down during this period, and 1 means the unit is turned on. Taking into account the economics of pumped storage power station operation, it is required that the unit cannot generate power and pump water at the same time, so there is: \( x_{j,t} + y_{j,t} \leq 1 \).

3. Model solving algorithm

In the wind-solar-hydro-thermal pumped-storage dispatch model constructed in Section 2, wind, solar, and natural runoff process are all deterministic input information. Therefore, this chapter mainly solves the difficult problems of multi-objective, nonlinear and high-dimensional models. Multi-objective model is a hot field in the existing optimization dispatch research. Most direct search methods transform the multi-objective optimization problem into a single-objective optimization problem, which can be solved by single-objective optimization methods. But this method can only get one solution at a time. Although it is possible to obtain multiple solutions by running the algorithm multiple times, there is no guarantee that these solutions will be uniformly distributed in the target space, and in non-convex problems, the Pareto optimal solution cannot be guaranteed. In the optimal dispatch model of the integrated energy system proposed in this paper, some of the constraints are non-convex and nonlinear, so solvers such as CPLEX or Gurobi cannot be used directly for calculation, while genetic algorithms can effectively deal with such problems. The traditional multi-objective genetic algorithm has the problem that the number of Pareto optimal solutions searched per unit time is small, and it is difficult to deal with multiple equality constraints.

Before the NSGA-II algorithm was proposed, NSGA was a very popular multi-objective genetic algorithm, but it has the following shortcomings: 1) High computational complexity; 2) No elite mechanism; 3) Need to specify shared parameters \( \pi \). Therefore, in this paper, NSGA-II uses fast non-dominated sorting methods, density estimation and crowded comparison operators to solve the above problems. Compared with the NSGA method, the main improvements of NSGA-II are as follows: 1) A
fast non-dominated sorting method is proposed. Compared with NSGA's non-dominated sorting, its computational complexity is greatly reduced. 2) The density estimation and crowded comparison operators are proposed to replace the shared parameter operation, which reduces the computational complexity.

4. Example Analysis
In order to verify the effectiveness of the model and algorithm in this paper, all wind farms, solar power stations and 4 thermal power plants in a certain area in southwest China, as well as 5 runoff hydropower stations, 2 cascade hydropower stations, and 1 pumped storage are equivalently configured for the convenience of analysis. The power station is the research object, and the operation data of load and power generation of each power source on the typical days of March 15, 2020 and June 15, 2020 are used for analysis. According to the following steps, the NSGA-II algorithm is used to calculate the multi-objective optimization dispatch of wind, solar, hydro, thermal, and pumped storage for energy saving and emission reduction. First, set the algorithm parameters. The Pareto frontier individual coefficient is set to 0.25; the population size is set to 100; the maximum evolution generation number is set to 2000; the stopping generation number is 200; the fitness function value deviation is 1e-100; and the wind turbine's demand coefficient for the conventional unit spinning reserve is set to 0.2.

Figure 1 Wind and Solar power characteristics
The predicted values of wind power, solar are shown in Figure 1. Solar output is concentrated in the daytime, and the general trend of solar power generation in different seasons is the same, and it is consistent with the load change direction, which has a positive peak regulation effect. The typical daily output is the largest in summer and the smallest in spring. Wind power generation has strong randomness, so the wind power output varies greatly within a single day, has anti-peak regulation characteristics, and differs greatly from season to season.

In order to optimize the power of pumped storage unit and optimize the capacity of the combined power generation system, it is necessary to optimize the power of pumped storage units for optimization of the power of pumped storage units and the output of the new energy. During the summer flood season, in order to ensure the safety of power consumption in flood season, when the hydropower station is full, priority should be given to hydropower and solar power generation to adjust the wind power and thermal power output to meet the load demand. By adjusting the penalty coefficient of power abandonment, the system abandons wind first, then solar, and finally hydro. In order to reduce the abandoned electricity and stabilize the fluctuation of thermal power, if the sum of the predicted output of renewable energy and the lower limit of thermal power output is greater than the predicted load, the pumped storage is in the state of pumping, generating power at the peak time of thermal power generation will stabilize the fluctuation of thermal power and reduce the total cost of the system. Figure 2 and Figure 3 are the optimization results.
When renewable energy is connected to the grid, solar power generation has the strongest load tracking ability. During the day, solar power generation is positive peak regulation. Wind power generation has strong randomness and has a certain anti-peak regulation. At this time, after adding pumped storage, it can better track the peak load period. Due to the large fluctuations in the output of new energy in different seasons, the requirements for the peak regulating capacity of thermal power units are also high. The solar output in summer is large, and the hydropower output is also large in the wet season. The addition of pumped storage can effectively reduce the cost and increase the economy. In addition, power is provided during the peak load at night in summer to reduce the volatility of thermal power units.

Table 1 Optimization results under different objectives

| Typical day | Total system cost / 10,000 yuan | Volatility / MW |
|-------------|--------------------------------|-----------------|
|             | No pumped storage | With pumped storage | No pumped storage | With pumped storage |
| March 15    | 1123.54            | 1014.12           | 3,675.32         | 2,897.21         |
| June 15     | 1089.21            | 1001.24           | 3,897.54         | 2,798.32         |

The results show that: ① Compared with the existing hydropower dispatching model, the multi-objective optimization model proposed in this paper takes into account the full utilization of hydropower and the utilization of the flexible peak regulation capability of hydropower; While reducing coal consumption and power generation costs, it also reduces the fluctuations in the output of each thermal power unit, and improves the safety and economy of system power generation; ② The NSGA-II multi-objective optimization algorithm used has multiple constraints and multiple objective functions and it is very adaptable. The simulation results show that the model and method proposed in this paper are reasonable and have certain practicability.

5. Conclusion
(1) The multi-energy system dispatching method with renewable energy constructed in this paper can not only effectively improve the consumption of renewable energy, but also effectively reduce the consumption of non-renewable energy such as thermal power, save the cost of power generation and
achieve the multi-energy power system daily joint optimization dispatch.

(2) The addition of pumped storage power stations can reduce the output of thermal power units, the operating costs of thermal power units, and the climbing costs of thermal power units due to fluctuations, and improve system economy.

(3) Due to the randomness and volatility of wind power processing and the day and night shutdown of solar power plants, the addition of pumped storage power plants can smooth the fluctuations in load and the uncertainty of wind power and solar power generation, and reduce the flexibility of the grid system to thermal power plants. It provides a dispatch strategy for the operation of multi-energy complementary systems with pumped storage.

References
[1] Chazarra M, Perez-Diaz JI, Garcia-Gonzalez J, Praus R. Economic viability of pumped-storage power plants participating in the secondary regulation service. Appl Energ. 2018;216:224-33.
[2] Chaudhary P, Rizwan M. Energy management supporting high penetration of solar photovoltaic generation for smart grid using solar forecasts and pumped hydro storage system. Renew Energ. 2018;118:928-46.
[3] Menendez J, Manuel Fernandez-Oro J, Loredo J. Economic Feasibility of Underground Pumped Storage Hydropower Plants Providing Ancillary Services. Appl Sci-Basel. 2020;10(11).
[4] Cheng C, Su C, Wang P, Shen J, Lu J, Wu X. An MILP-based model for short-term peak shaving operation of pumped-storage hydropower plants serving multiple power grids. Energy. 2018;163:722-33.
[5] Liang N, Deng C, Chen Y, Yao W, Li D, Chen M, et al. Two-Stage Coordinate Optimal Scheduling of Seawater Pumped Storage in Active Distribution Networks. Sustainability-Basel. 2018;10(6).
[6] Sun K, Li K, Pan J, Liu Y, Liu Y. An optimal combined operation scheme for pumped storage and hybrid wind-photovoltaic complementary power generation system. Appl Energ. 2019;242:1155-63.
[7] Wang Y, Zhao M, Chang J, Wang X, Tian Y. Study on the combined operation of a hydro-thermal-wind hybrid power system based on hydro-wind power compensating principles. Energ Convers Manage. 2019;194:94-111.
[8] Patwal RS, Narang N. Multi-objective generation scheduling of integrated energy system using fuzzy based surrogate worth trade-off approach. Renew Energ. 2020;156:864-82.
[9] Su C, Cheng C, Wang P, Shen J, Wu X. Optimization model for long-distance integrated transmission of wind farms and pumped-storage hydropower plants. Appl Energ. 2019;242:285-93.
[10] Xu X, Hu W, Cao D, Huang Q, Chen C, Chen Z. Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. Renew Energ. 2020;147(1):1418-31.