Optimization scheduling model and method for Wind-PV-Pumped joint operation in high proportion renewable energy base

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Abstract. Aiming at the uncertainty of wind and PV output and the fluctuation of wind and PV grid connection output, an optimized scheduling model and method for wind-PV-pumped storage combined operation in high proportion renewable energy base is proposed. Firstly, the optimal scheduling model for 96 periods of the whole day was established with the objective of optimal comprehensive benefit, minimum power fluctuation and optimal power demand matching of the wind-PV-pumped storage co-generation system. Then, an NSGA-III algorithm more suitable for high-dimensional multi-objective optimization is introduced to obtain Pareto optimal solution set of co-generation system. Finally, the simulation of jiuquan new energy base was carried out to verify the effectiveness of the proposed model.

1. Introduction
At present, the energy storage system with the wind, photovoltaic power generation's attention and research way and pumped storage energy storage due to its relatively mature technology unit capacity cost is relatively low and the ability to mass storage, become an important way and wind-PV joint operation of literature[1] has set up a model for the scenery complementary battery, combined with wind power system was discussed and the photoelectric model in grid and island mode of operation, the results show that the joint operation system can effectively reduce the and node voltage fluctuations, but not considering the volatility of system output. Literature[2] in the isolated net system scenery complementary pumped storage power generation model, the net load is greater than zero is equal to zero and less than three kinds of circumstances to determine the operation mode of pumped storage unit, but not to do further discussion to the stability of the system. Literature[3] of water scenery complementary operation schemes are discussed, comparison and analysis the scenery complementary scenery water pumped storage operation scheme mixed operation scheme of three ways, finally it is concluded that water and wind energy complementary development of wind power station and photovoltaic grid problem can be solved, a reasonable scheduling of the wind power and photovoltaic power station, improve the efficiency of energy use, but not considering the economic benefits of the system. Literature[4] in the wind-PV-pumped storage power station system in an interactive optimization model is put forward, the multi-objective optimization problem by a single goal satisfaction function and overall coordination degree evaluation function into a single objective optimization problem to solve, the optimization goal for the weighted sum of each target, conflicting goals will complicate the topology of the weighted targets.
According to the above problem, this paper established the wind-PV-pumped storage optimization scheduling model, the economic benefits of combined power generation system matching coordinated optimization of power fluctuations in power demand, building 1, 96 hours of joint optimization scheduling model, and according to the non dominated sorting algorithm based on the reference point is analyzed with numerical wind-PV-pumped storage optimization scheduling model effectively restrain the system power fluctuations, is advantageous to the power grid scheduling and the safe and stable operation, and validate the proposed model has good feasibility.

2. Wind-PV-pumped storage joint optimization model

2.1 Wind-PV-pumped storage combined operation scheme

Because of the wind and photoelectric is not very stable output power, energy storage and pumped storage power station and the characteristics of rapid adjustment, in the process of research, this paper chose the wind power and photovoltaic power station joint pumped-storage power station has set up a three complementary system in operation and related structures are shown in figure 1.

Under the joint operation mode, the operation objectives of pumped storage power station are as follows: maximizing the daily operating income; with wind-PV power supply, the deviation between actual output data and predicted data caused by sudden change of wind-PV output is compensated to a certain extent.

![Figure 1. Principle diagram of wind-PV-pumped storage joint operation](image)

2.2 The goal is to maximize benefits

Taking the efficiency maximization of wind-PV-pumped storage joint operation as the goal, considering the start-up and shutdown costs of the generator set in the pumped storage power station and the penalty of deviation from the output plan, the objective function is:

\[
\text{f}_i = \sum_{i}^{96} \left[ C_i \left( p_{wi} + p_{vi} + p_{pi} P_{pou} \right) C_{su} n_{ij}^{su} - C_{ed} n_{ij}^{ed} - \omega C_i \left( p_{wi} + p_{vi} + p_{pi} P_{pou} - P_{li} \right) \right] \tag{1}
\]

Where: \( i \) represents the time series, taking 15min as a time period; \( i = 1, 2, \ldots, 96 \); Consider the change of electricity price in different periods; \( C_i \) is the on-grid electricity price of period \( i \); \( p_{wi} \) is the wind turbine output in period \( i \); \( p_{vi} \) is photovoltaic power station output in period \( i \); \( p_{pi} \) is the total output of the pumped storage power station generator set in period \( i \); \( P_{pou} \) is the total pump pumping power of the pumped storage power station in period \( i \); \( \omega \) is the penalty coefficient of output deviation; \( P_{li} \) is the planned output of the joint operation of wind-PV-pumped storage power station in period \( i \); \( C_{su} \) and \( C_{ed} \) is the pump start/stop cost; \( n_{ij}^{su} \) and \( n_{ij}^{ed} \) is the number of starting/stopping water pump units in period \( i \).

2.3 Aim to minimize the power fluctuation of the co-generation system

In order to characterize the restraining effect of composite energy storage on the power fluctuation of renewable energy generation, the optimization objective function was established in this paper to
minimize the sum of squares of the difference in power variation of renewable energy after adjustment, as follows:

\[ f_2 = \sum_{i=1}^{n_2} \left( p_{wi} + p_{vi} + p_{pi} - p_{pol} - p_{Li} \right)^2 \]  \hspace{1cm} (2)

Where, \( f_2 \) represents the sum of squares of the power variation difference of renewable energy; \( i \) represents time series; \( p_{wi} \) is the wind turbine output in period \( i \); \( p_{vi} \) is pv power station output in period \( i \); \( p_{pol} \) is the total output of the pumped storage power station generator set in period \( i \); \( p_{Li} \) is the total pump pumping power of the pumped storage power station in period \( i \), and \( p_{Li} \) is the planned output for the joint operation of the wind-PV-pumped storage power station in period \( i \).

2.4 aim at optimal power demand matching of the joint system

The combined system output power should match the given generation plan. If the energy storage capacity is insufficient, the surplus electric energy will be released through the unloading device, resulting in energy waste. When the power generation is insufficient, the load must be dumped, which reduces the power supply reliability of the integrated system.

\[ f_3 = \sum_{i=1}^{n_6} \left( p_{Li} - p_{ni} \right)^2 \]  \hspace{1cm} (3)

Where, the objective function \( f_3 \) represents the sum of the squares of the difference between the output power of the combined system and the given generation plan within one day after the use of the pumped storage power station. \( p_{Li} \) is the planned output of the joint operation of wind-PV-pumped storage power station in period \( i \); \( p_{ni} \) represents the load forecast value of time period \( i \) of the day.

In conclusion, the multi-objective optimization mathematical model of wind-PV-pumped storage combined system is as follows:

\[ f = \begin{cases} \max f_1, \\ \min f_2, \\ \min f_1 \end{cases} \]  \hspace{1cm} (4)

The constraint conditions of the model are shown in equation (5) - (12):

A. Capacity constraint of pumped storage power station:

\[ V_{u,\min} \leq V_i^u \leq V_{u,\max} \]  \hspace{1cm} (5)
\[ V_{d,\min} \leq V_i^d \leq V_{d,\max} \]  \hspace{1cm} (6)
\[ \delta_{\min} \leq V_{0,\max} - V_i^u \leq \delta_{\max} \]  \hspace{1cm} (7)

Where: \( V_{u,\min} \), \( V_{u,\max} \), \( V_{d,\min} \), \( V_{d,\max} \) are the minimum and maximum capacity of the upper and lower reservoirs respectively; \( V_i^u \) and \( V_i^d \) is the actual storage capacity of upper and lower reservoirs in period \( i \), \( V_0^u \) and \( V_0^d \) is the initial capacity of the upper and lower reservoirs; \( \delta_{\min} \) and \( \delta_{\max} \) is the minimum and maximum variation of storage capacity at the beginning and end of each day.

Power constraints for turbines and pumps:

\[ n_i^p \leq N \]  \hspace{1cm} (8)
\[ n_i^p p_{min} \leq p_{pol} \leq n_i^p p_{max} \]  \hspace{1cm} (9)
\[ g_{min} \leq p_{pi} \leq (N - n_i^p) g_{max} \]  \hspace{1cm} (10)
(1 - ε) p_i ≤ p_{pi} + p_{wi} + p_{pot} ≤ (1 + ε) p_{ti} \quad (11)

\sum_{i=1}^{Q} (n_i^{su} + n_i^{sd}) ≤ 2N \quad (12)

Where: \( n_i^p \) is the number of pumping units at time \( i \), \( N \) is the number of reversible pumping - generating sets available in a pumped storage power station, \( p_{min} \) and \( p_{max} \) is the upper and lower limits of pumping power of a single unit, \( g_{min} \) and \( g_{max} \) is the pumped storage power station unit output limit, \( \epsilon \) is the deviation coefficient of a given load.

3. To solve the model

In this paper, nondominant sorting algorithm (NSGA-III algorithm) based on reference points is adopted for multi-objective optimization. NSGA-III algorithm was proposed by Kalyannoy Deb in 2014 [13]. On the basis of NSGA-II algorithm, the concept of reference point is introduced to improve the convergence of the algorithm and the distribution uniformity of the optimal solution. As the selection mechanism based on crowded distance in NSGA-II was abandoned, the selection mechanism based on reference points was replaced to ensure the diversity of understanding, which was especially suitable for solving optimization problems with three or more objectives.

4. Case analysis

4.1 Example system

This paper uses the node system of Jiuquan City in Gansu Province as the basis of the example, and analyzes the parameters of the Jiuquan Changma Pumped Storage Power Station in Gansu Province. The pumped storage power station is equipped with four reversible water pump-turbine units with a rated power of 300 MW. The wind power output, photovoltaic output and load prediction curve of the system are shown in figure 2 and 3.

The power parameters of a single pump and turbine group, the installed capacity of wind and optical electric fields, and the storage capacity of the reservoir are shown in Table 1.

| Parameter                              | Value     |
|----------------------------------------|-----------|
| Wind turbine cut wind speed \( v_{ci} \) \( m/s \) | 2.50      |
| Cut out of the wind speed \( v_{co} \) \( m/s \) | 25.00     |
| Photovoltaic power station photoelectric conversion efficiency \( \eta_{ph}/W\cdot m^2 \) | 0.15      |
| The area of a single panel \( A_m \) \( m^2 \) | 1.0       |
| Generating coefficient of hydropower station \( \eta_{g}/kW\cdot h/m^3 \) | 0.2       |
| Pumping station pumping coefficient \( \eta_{p}/m^3/kW\cdot h \) | 3.75      |
The upper reservoir holds water $P_u \text{ m}^3 \quad 7.27 \times 10^6$

Normal water level of upper reservoir m 2807

The lower reservoir holds water $P_l \text{ m}^3 \quad 7.28 \times 10^6$

The normal water level of the lower reservoir m 2375

4.2 Results and analysis

The parameters of the NSGA-III algorithm are set as follows: the population size and the number of iterations are 100, the percentage of the individual and the percentage of the crossover are both 50%, and the probability of variation is 0.02, $p = 7$ (ie, 120 reference points are generated). Table 2 lists some of the more representative Pareto solutions.

| Combined system benefits/(Wanyuan) | Sum of power fluctuations $\text{MW}^2$ | Sum of squares of load differences $\text{MW}^2$ |
|-----------------------------------|----------------------------------------|-----------------------------------------------|
| 105.79                            | 1997                                   | 912                                           |
| 113.42                            | 2125                                   | 1023                                          |
| 116.55                            | 2279                                   | 1044                                          |
| 125.73                            | 2684                                   | 1120                                          |
| 138.12                            | 2946                                   | 1463                                          |
| 167.33                            | 3595                                   | 2886                                          |

It can be seen from table 2. that the three targets set in this paper cannot achieve optimality at the same time. It is impossible to achieve the optimal ideal solution at the same time between increasing economic efficiency and reducing power fluctuation, and the reduction of power fluctuation is at the cost of reducing economic benefits.

The combined output of wind and light, the output of pumped storage power station, and the combined output of wind-PV-pumped storage are shown in figure 4. It can be seen from the figure that the pumped storage unit generates electricity by pumping water during the low load period (1st to 24th and 60th to 78th periods) and during the peak load period (32th to 52nd and 80th to 89th). The peak-to-valley difference of the system net load can be reduced, so that the output of the unit with lower power generation cost in the low valley period is increased, and the output of the unit with higher power generation cost in the peak period is reduced, thereby reducing the output cost of the conventional unit as a whole.
4.3 Analysis of joint operation mode
The wind storage combined system, the optical storage combined system, the wind-PV-pumped storage combined system, and the power generation system are analyzed, and the power characteristics of the grid-connected points during grid-connected operation are shown in figure 5.

The initial active output of wind power is 1400 MW, which fluctuates by up to 150 MW between 10 and 20 s due to the volatility of wind power. The initial output of the PV system is 720 MW, with power fluctuations of up to 140 MW in 8-11 s. It can be seen from the overall fluctuation trend of the power curve in Fig.7 that the overall fluctuation of the output of the wind-PV-pumped storage combined power generation system is reduced, but the phenomenon of instantaneous power fluctuation still exists. The system instantaneously sends active power fluctuations up to 50MW. The active output range of the wind-PV-pumped storage combined power generation system ranges from 1340 MW to 1450 MW.

It can be seen from the above analysis that the wind-PV-pumped storage combined power generation system has wind-PV complementary characteristics as a whole, which can effectively cope with the output power fluctuation of the wind-PV system, and is conducive to grid dispatching and safe and stable operation.

5. Conclusion
In this paper, the wind-PV-pumped storage combined power generation system has the best comprehensive benefit, the power fluctuation of the combined power generation system is the smallest, and the power demand matching is the best. It is closely combined with the Jiuquan new energy base and establishes the daily optimal dispatch of 96 time periods throughout the day. The model is analyzed by the example system of Jiuquan City, Gansu Province, and the following conclusions are obtained:

1) This paper studies the multi-objective modeling problem of wind-PV-pumped storage combined power generation system, and achieves multiple objectives with the goal of optimal comprehensive benefit, minimum power fluctuation of combined power generation system and optimal power demand matching. Balance between the two.

2) The wind-PV-pumped storage system operates in different combinations. It is verified that the wind-PV-pumped storage combined power generation system effectively suppresses the power fluctuation of the wind-light system, which is conducive to grid dispatching and safe and stable operation.

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