A joint optimal dispatching method of wind-solar-hydro generation system

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Abstract. As the first choices among new energy resources to alleviate the crisis of fossil fuels and solve the problem of environmental pollution, wind and solar power generation have attracted more and more attention. However, the instability and intermittency of its output have become the bottleneck restricting its large-scale development. In the system with wind and PV power, conventional energy is often required to reduce the volatility of the output. Due to the characteristics of stable output and quick response to load change, the cascade hydropower station compensates the instability of wind and solar power output. In this paper, a combined generation model including wind power, photovoltaic generation and the cascade hydropower stations has been built and NSGA-II has been used to work out a scheduling scheme, which has been proved to perform better than other algorithms.

1. Introduction
Wind energy is a renewable clean energy, compared with fossil fuels power, wind power can reduce environmental pollution and improve the energy structure. In the long run, the wind on the economy has already been able to compete with conventional energy [1]. However, wind power output is closely related to wind speed. When large-scale wind power is grid-connected, the fluctuation and uncontrollability increase the prediction error of wind power output. The system backup needs to take both load forecasting error and wind power forecasting error into account, which increases the difficulty of scheduling [2].

Solar energy is also renewable and pollution-free. Its clean, environmentally friendly, flexible and storable features make it widely used in community, school, hospital and other distributed power systems. Many countries are also trying to dominate the research and development of the photovoltaic power industry. However, like wind energy, due to the high dependence on environment and temperature, photovoltaic power generation has a strong intermittent and randomness, and its output is 0 at night when there is no light. At the same time, as the core of photovoltaic power generation, photovoltaic cells have a high cost and the efficiency of photoelectricity conversion needs to be improved [3]. If photovoltaic power generation is to be applied on a large scale, these two problems must be solved.

In conclusion, wind and PV power generation still has the problems of technology and scale, and its uncertainty and volatility bring some difficulties to dispatch. Thus, it is necessary to find other energy to compensate for the drawbacks of the wind and PV power.

In the electric power system containing wind power, photovoltaic power generation, thermal power units often make up for the output volatility of the system, but frequent alteration of thermal power
unit load reduces the service life of the thermal power units and increases operation maintenance costs. China is rich in water resources and its reserves rank first in the world. Large-capacity hydropower units are equipped with high stability, strong peak shaving ability, high safety and environment-friendly ability. In large hydropower stations, the fluctuation of water is suppressed by the reservoir's water storage, which keeps stable outputs. Compared with thermal power units, hydropower units have a short start and stop time and can be adjusted quickly. The operation process from shutdown to rated load operation can usually be completed within a few minutes. It is noteworthy that the operation modes of hydropower stations change according to wet and drought seasons. At the same time, when the cascade hydropower station is involved in the dispatching, its constraint conditions are quite complex that it is necessary to take both the reservoir capacity constraint, the output constraint, the generation flow constraint and the upstream and downstream hydraulic connection into account [4].

To improve guidelines for large-scale hydro–PV plant operation, a stochastic hydro unit commitment model considering the uncertainty in forecasting PV power has been presented by Bo M [5]. A mixed-integer non-linear mathematical model has been developed by Jakub Jurasz for simulating the integrated operation of a novel hybrid involving wind- and solar power and a hydroelectric power station with pumping installation [6]. However, there are few articles taking cascaded hydropower stations into account, thus in this paper, cascaded hydropower stations have been combined with PV and wind generation to make sure more stable outputs of the power system.

To sum up, hydropower can make up for the shortage of new energy power generation such as wind and PV power generation, which makes the scheduling structure more reasonable. Combined with the actual power grid structure in Qinghai, China, in this paper, the interaction mechanism and optimal scheduling mode of multi-energy have been deeply studied, and the reasonable joint optimal scheduling model has been improved.

2. Calculation of the joint energy system

2.1. Calculation of wind power generation

The premise of studying the operation state of wind power plant and the output power characteristic of wind power unit is to get the output power of wind power unit. The output power of the unit is a function of wind speed and is proportional to the wind speed. The swept area of the blade, i.e. the impeller radius, determines the wind energy that can be captured by the fan. The power absorbed from the wind can be expressed by formula (1).

\[ P_w = \frac{1}{2} \rho \pi R^2 C_p \nu^3 \] (1)

In formula (1), \( P_w \) represents the output power of the wind power units; \( \rho \) is the air density; \( R \) is the radius of the impeller (\( \pi R^2 \) is the swept area of blade); \( C_p \) represents the coefficient of the wind energy utilization factor whose maximum value is 0.593; \( \nu \) represents the velocity of wind which is expressed by formula (2).

\[ \nu = \nu_1 \left( \frac{h}{h_l} \right)^n \] (2)

In formula (2), \( h \) represents the height between the ground and the point whose velocity is unknown; \( h_l \) represents the height between the ground and the point whose velocity is already known; \( \nu \) is the wind velocity at \( h \); \( \nu_1 \) is the wind velocity at \( h_l \).

In practical wind power engineering, output power – wind velocity curve is preferred to reflect the treatment characteristics of wind power units. The curve is shown in the Figure 1.

The relationship between wind power output and wind speed is shown as formula (3).

\[ P_w = \begin{cases} 0 & (\nu < \nu_{c1} \text{ or } \nu > \nu_{c2}) \\ \alpha \nu^k + b & (\nu_{c1} < \nu < \nu_{c2}) \\ P_r & (\nu_{c2} < \nu < \nu_{c3}) \end{cases} \] (3)
In formula (3), $P_r$ is the rated output power; $v$ is the actual wind velocity; $v_{ci}$ is the cut-in wind velocity; $v_r$ is rated wind velocity; $v_{co}$ is cut-out wind velocity; $a$ and $b$ are fitting curve parameters provided by the manufacturer.

2.2. Calculation of PV power generation
The power - voltage curve of the photovoltaic cell varies with the radiation intensity and temperature conditions [7]. Experiments show that the relationship between solar cell characteristics, radiation intensity and ambient temperature is highly non-linear, and the output power of PV array has a maximum point at different radiation intensity and ambient temperature. Under the reference conditions, when the PV array voltage is $U$, its corresponding output power is shown as formula (4).

$$P = U I_{sc} \left[ 1 - C_1 \left( \frac{U}{E_{oc}} - 1 \right) \right]$$

In formula (4), $I_{sc}$ is short circuit current, $U_{oc}$ is open circuit voltage. $C_1$ and $C_2$ is the correlation coefficient.

2.3. Calculation of cascade hydropower generation
As a nonlinear programming problem with complex constraints, optimal operation of cascade hydropower stations is always a key and difficult problem. In addition to the power load balance, the constraint conditions should also consider the generation flow constraint, generation power constraint, initial and final storage capacity constraint, upstream and downstream hydraulic connection and natural water inflow of each hydropower station. When the number of hydropower stations in the same river basin increases, the high-dimensional and nonlinear relation of the problem becomes more obvious, which further increases the difficulty of solving the problem. At the same time, the changeable extreme climate disasters decide the flexibility of the treatment plans.

The power generation flow quantity of the upper hydropower station and the discharge of water affect the output of the lower hydropower station. At the same time, in the cascade hydropower station, there is a time delay when the flow of the upper hydropower station reaches the lower hydropower station [8]. Therefore, different from many hydropower stations without hydraulic connection, the hydraulic connection of upstream and downstream power stations in the same basin needs to be considered in addition to power distribution among cascade hydropower stations. The fitting calculation formula of active power of the $j$th hydropower station is expressed as formula (5).

$$P_{hj} = c_1 v_{hj}^2 + c_2 Q_{hj} v_{hj}^2 + c_3 V_{hj} Q_{hj}^2 + c_4 Q_{hj} + c_5 Q_{hj} + c_6$$
In formula (5), \( c_i \) \((i = 1,2,3,4,5,6)\) represents the power generation fitting coefficient; \( V_{hj} \) represents the volume of the \( j^{th} \) hydropower station; \( Q_{hj} \) represents the quantity of the flow of the \( j^{th} \) hydropower station.

3. Mathematical model of the joint energy system

3.1. Optimization model

The purpose of integrate wind power, PV power and hydro power is to avoid the uncontinuity and instability caused by wind velocity and solar radiation. The total power output of the wind/PV/hydro hybrid system is expected to be reliable with variation as small as possible. On the other hand, the power generation of the whole system should be maximized by regulation of the cascade hydropower stations. Therefore, there are two objectives selected in this study, as illustrated below. There are two objectives in the optimization model.

Objective 1: minimizing the variance of the power output

In order to guarantee the smoothness of the output of the power grid, the fluctuation of the power output should be as small as possible [9]. Thus, minimizing the variance of the power output of the hybrid system is selected as an optimizing objective, as described in formula (6):

\[
obj_1 = \text{Min} \sum_{t=1}^{T} \frac{(p^t - \bar{P})}{T}
\]  

In formula (6), \( T \) is the total number of time periods being calculated, \( P \) is the total power output of the wind/PV/hydro hybrid power system, \( P = P_{w} + P_{pv} + P_h \); and \( \bar{P} \) is the average value of \( P \) during the time period.

Objective 2: maximizing total generated energy of the wind/PV/hydro hybrid system

Maximizing power generation of the whole system in the entire time period is an important operational objective for any power generation system. The objective function can be written as formula (7):

\[
obj_2 = \text{Max}(E) = \text{Max} \sum_{t=1}^{T} (P_{w}^t + P_{pv}^t + P_h^t) \times \Delta t
\]

In formula (7), \( E \) is the total generated energy.

3.2. Constrain

The main operational constraints of the hybrid system include the constrains of reservoir pool level, reservoir release, as well as the capacity of the power grid to accommodate the power energy, as shown in formula (8)-(10):

\[
t_{min}^t \leq t^t \leq t_{max}^t \quad (8)
\]

\[
Q_{min}^t \leq Q^t \leq Q_{max}^t \quad (9)
\]

\[
p^t \leq A \quad (10)
\]

In formula (8)-(10), \( t_{min}^t \) and \( t_{max}^t \) are the allowable lowest and highest level during time \( t \), respectively; \( Q_{min}^t \) and \( Q_{max}^t \) are the lower and the upper limit of the reservoir release, respectively; and \( A \) represents the ability of the power grid to accommodate energy.

4. Optimization algorithm

The model is solved by NSGA-II. The specific steps of the model were listed as the following:

Step 1: Initialize the population, \( P_h \) are the variables of the optimization; Step 2: Crossover, mutate and the new population is generated; Step 3: Non-dominated sort; Step 4: Calculate the crowding
distance; Step 5: If the stop condition can be met; if so, the new population is the Pareto front; if not, update the population and turn to Step 2. The flow chart of the model is shown in Figure 3.

5. Case studies

5.1. Parameters
As an example, the hybrid system with wind power plant, a photovoltaic power station and four cascade hydropower stations were simulated. Basic parameter setting: population evolution time was 1000, population size was 50, individual crossover probability was 0.8, Table 1 shows the given parameters of cascade hydropower station which were cited from [7].

![Figure 3. Multi-objective optimization of wind/PV/hydro hybrid system.](image)

![Figure 4. Optimal solution nearest to the ideal state.](image)

| Hydropower station | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $c_6$ |
|-------------------|------|------|------|------|------|------|
| 1                 | -0.0042 | -0.42 | 0.03 | 0.9 | 10 | -50 |
| 2                 | -0.004 | -0.3 | 0.015 | 1.14 | 9.5 | -70 |
| 3                 | -0.0016 | -0.3 | 0.014 | 0.55 | 5.5 | -40 |
| 4                 | -0.003 | -0.31 | 0.027 | 1.44 | 14 | -90 |

5.2. Results
Table 2 presents the statistic results of the objectives on the Pareto Front in different typical years. Generally, the variance of the hourly power output is larger in wet years than in dry years, since there is abundant water for dynamic adjustment, which also results in larger power generation in wet years. It can be seen that the optimization is inclined to maximize the power output efficiency with large amount of water.

Pareto solution set of this group is sorted on the basis of TOPSIS based on entropy weight method, so as to select the optimal non-inferior solution and obtain the optimal scheduling scheme, which is shown in table 3. The output size of PV power, wind power and cascade hydropower station within 24 hours is shown in the table. Figure 5 intuitively shows the output of various power sources in the entire scheduling period. Within 24 hours, the output adjustment of cascade hydropower station is flexible and rapid, which can well respond to the changes of load.
Table 2. Statistics of the Pareto Front for different years

| Year        | Variance of the hourly power output (× 10^4kW^2) | Daily power generation (× 10^6kWh) |
|-------------|-----------------------------------------------|------------------------------------|
|             | Min | Max | Mean | STD | Min | Max | Mean | STD |
| 1989 (Wet)  | 38.23 | 47.84 | 42.75 | 2.84 | 22.27 | 23.75 | 23.07 | 0.44 |
| 1993 (Wet)  | 26.76 | 34.20 | 29.96 | 2.06 | 19.67 | 20.99 | 20.41 | 0.38 |
| 1996 (Dry)  | 18.04 | 24.46 | 20.68 | 1.93 | 15.62 | 16.52 | 16.14 | 0.25 |
| 1998 (Normal)| 24.77 | 30.88 | 27.58 | 1.81 | 19.48 | 20.41 | 19.97 | 0.27 |
| 2000 (Dry)  | 22.69 | 29.65 | 25.42 | 2.16 | 17.56 | 18.79 | 18.33 | 0.36 |

Table 3. TOPSIS optimal scheduling scheme based on entropy weight method

| t   | Wind power (MW) | PV power (MW) | Hydropower (MW) | Overall load (MW) |
|-----|-----------------|--------------|-----------------|-------------------|
| 0:00| 112             | 0            | 658             | 770               |
| 1:00| 105             | 0            | 659             | 764               |
| 2:00| 120             | 0            | 665             | 785               |
| 3:00| 105             | 0            | 673             | 778               |
| 4:00| 105             | 0            | 662             | 767               |
| 5:00| 95              | 0            | 686             | 781               |
| 6:00| 84              | 14           | 707             | 805               |
| 7:00| 98              | 28           | 672             | 798               |
| 8:00| 112             | 42           | 697             | 851               |
| 9:00| 80              | 70           | 707             | 857               |
| 10:00| 32             | 112          | 721             | 865               |
| 11:00| 35             | 119          | 714             | 868               |
| 12:00| 35             | 133          | 701             | 869               |
| 13:00| 48             | 126          | 686             | 860               |
| 14:00| 66             | 119          | 669             | 854               |
| 15:00| 78             | 105          | 666             | 850               |
| 16:00| 118            | 70           | 644             | 832               |
| 17:00| 126            | 42           | 671             | 839               |
| 18:00| 140            | 21           | 645             | 806               |
| 19:00| 154            | 0            | 641             | 795               |
| 20:00| 158            | 0            | 685             | 843               |
| 21:00| 143            | 0            | 700             | 843               |
| 22:00| 140            | 0            | 700             | 840               |
| 23:00| 132            | 0            | 665             | 797               |
| 0:00| 112             | 0            | 658             | 770               |

The Pareto optimal solutions were normalized, and the one approaches the closest to the ideal state is picked out to provide a reference for the operation, as illustrated in Figure 4. The two objectives show an apparent counterbalance relationship. For a particular year, to maximize the total power generation needs to enhance the output efficiency by increasing water release in the time periods with high water head, which leads to power output variation. It can be seen that for the study case the hydropower plays leading roles in the hybrid power system, and the inflow condition determines the annual power generation.

As can be seen from Figure 5, hydropower smooths the fluctuation of load, wind output and PV output. It has remarkable effect on tracking load change and compensating for the fluctuation of wind power output. During 0:00-5:00 and 19:00-24:00, the output of the photovoltaic power station is 0, and the system load is jointly shared by wind power, PV power and hydropower units. From Figure 6 it can be seen that the convergence speed and stability of PSO is better while the final convergence performance of NSGA-II is the best.
6. Conclusions
The crisis of fossil fuel depletion and the severe situation of environmental pollution make it urgent to change the energy structure. Wind and solar energy, two kinds of renewable energy, are clean and environmentally friendly, which can greatly improve resources and environmental problems. On the other hand, the output of these two new energy sources is very volatile and intermittent, which requires timely adjustment of the output of other power sources to stabilize the instability. In the power forecasting, both the traditional load forecasting error and the new energy forecasting error should be taken into account. Hydropower is clean energy and it is also stable and can be adjusted rapidly according to the load. This kind of energy can be used to curb the uncertainty of new energy output.

This study aimed to explore a short-term optimization model for wind/PV/hydro hybrid systems, considering the stability of the power output and the total power generation simultaneously. The PV power output is firstly worked out by hourly solar radiation, the result of which is taken as the boundary condition of the hydropower optimization. Taking the reservoir release as the decision variables, minimizing the variance of the power output and maximizing the daily power generation are then set as the objectives, which are optimized by NSGA-II. The application of the proposed model on a wind/PV/hydro hybrid power system verified its validity. The results proved that wind power hydropower and PV power complement each other in nature. The provided estimation of the power generation potential can be taken to evaluate the actual operation, as well as the reference for practice. The proposed methodology can also be generalized to other hybrid power systems than this case.

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