Research on Optimal Scheduling of Wind-PV-Hydro-Storage Power Complementary System Based on BAS Algorithm

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Abstract. In order to solve the impact of massive wind power and solar power’s grid-connection volatility on the safe and stable operation of the power grid. By analyzing the complementary characteristics of the wind power, solar power, hydro power and pumped storage power, regarding the wind power, solar power, hydro power and pumped storage power as an entire complementary generation system. Considering multiple power constraints, there proposes two optimal scheduling models with the minimum volatility of the complementary system and the minimum volatility of the thermal power unit equivalent load. Then we use the beetle antennae search algorithm to solve the two models. Simulation results indicate that the two optimal scheduling models can track the optimization objectives well and reduce the impact of wind and solar power’s connection to the power grid.

1. Introduction
With the increasingly serious problems of fossil energy crisis and environmental pollution, renewable energy with clean advantages has gradually become the focus of attention. A high proportion of renewable energy into the power grid has become a new development direction of power systems. However, both wind power and solar power generation have strong randomness, volatility and intermittence. Massive wind and solar power’s connection makes the safety and stability of power systems face severe challenges[1].

In recent years, there have been many studies on multi-energy complementary power generation. The multi-objective model of wind-solar-thermal power generation is proposed in [2]. And the validity and practicability of the model are verified by practical examples in China. Literature [3] studied the effects of time-complementary characteristics of solar and wind energy resources on the reliability of micro-hybrid systems from the perspective of covering fixed loads.

Based on the previous studies, this paper analyzes the complementary characteristics of wind-photovoltaic-hydro-storage system. Two optimization scheduling models are proposed based on the minimum output power volatility of complementary systems and the minimum volatility of thermal power units. The BAS algorithm simulates the optimal scheduling model. Simulation results indicate that the two optimal models can reduce the grid volatility caused by large-scale wind and grid integration and improve the energy efficiency of new energy sources.
2. Optimal scheduling of scenery and water storage complementary systems

2.1. Optimal scheduling model
The main purpose of the wind-photovoltaic-hydro-storage complementary system is to reduce the output fluctuation on power grid after wind and solar power’s connection to power system and improve the capacity of the power system.

2.2. Objective functions
The optimization goal is to minimize the output power volatility and minimize the equivalent load volatility of the thermal power unit.

1) Minimal complementary system output power volatility
\[
\text{min } F_1 = \frac{1}{T} \sum_{t=1}^{T} |P_{Re,t} - P_{av}| \tag{1}
\]
\[
P_{Re,t} = P_{W,t} + P_{PV,t} + P_{H,t} + P_{PS,t} \tag{2}
\]
Where: \(F_1\) is the complementary system’s output fluctuation power; \(P_{Re,t}\) is the \(t\)th output of the complementary system; \(P_{av}\) is the average output power in scheduling cycle; \(T\) is the number of time periods in scheduling cycle; the day-ahead scheduling is 24.

2) The minimum load fluctuation of thermal power unit
For further reducing the thermal power unit’s peak-shaving pressure to the residual load after the complementary system connected to the grid, we adjust the output of hydro power station and the pumped storage power station to make the complementary system’s output in line with the load.

For convenience, define the equivalent load \(P_{Leq,t}\) of the thermal power unit as the load \(P_{LtP}\) minus the complementary system output power \(P_{Re,t}\),
\[
P_{Leq,t} = P_{LtP,t} - P_{Re,t} \tag{3}
\]
\[
P_{Leq,av} = \frac{1}{T} \sum_{t=1}^{T} P_{Leq,t} \tag{4}
\]
\[
\text{min } F_2 = \frac{1}{T} \sum_{t=1}^{T} |P_{Leq,t} - P_{Leq,av}| \tag{5}
\]
Where: \(F_2\) is the fluctuation of the equivalent load of the thermal power unit, \(P_{Leq,t}\) is the equivalent load of the thermal power unit, and \(P_{Leq,av}\) is the average value of the equivalent load in one scheduling period.

2.3. Complementary characteristic analysis
1) Wind power constraint.
\[
0 \leq P_{W,t} \leq P_{W,\text{max}} \tag{6}
\]
Where: \(P_{W,t}\) is the \(t\)th period output of wind power plant, and \(P_{W,\text{max}}\) is the rated output of wind power plant.

2) Solar power constraint.
\[
0 \leq P_{PV,t} \leq P_{PV,\text{max}} \tag{7}
\]
Where: \(P_{PV,t}\) is the output of the photovoltaic power station in period \(t\), and \(P_{PV,\text{max}}\) is the maximum output power of the photovoltaic power station.

3) Hydro power station output constraint and storage constraint.
\[
P_{H,\text{min}} \leq P_{H,t} \leq P_{H,\text{max}} \tag{8}
\]
where: $P_{H_{\text{max}}}$, $P_{H_{\text{min}}}$ is the upper and lower limits of the hydropower station output, $P_{H,t}$ is the $t$th period capacity of the hydropower station, $E_H$ is the reservoir capacity.

4) Pumped storage capacity constraint and reservoir storage constraint.

\[
\begin{align*}
\max_{PS_{min}} & \leq P_{PS,t} \leq \min_{PS_{max}} \\
E_{r+1} & = E_r - \Delta E_r \\
\Delta E_r & = \begin{cases} 
\frac{P_{PS,t} \times \Delta t \times \min_{PS_{max}}}{\eta_g} & P_{PS,t} \geq 0 \\
\frac{P_{PS,t} \times \eta_d \times \Delta t \times \min_{PS_{max}}}{\max_{PS_{max}}} & P_{PS,t} \leq 0
\end{cases}
\end{align*}
\]

\[
E_{\text{min}} \leq E_r \leq E_{\text{max}}
\]

Where: $P_{PS,t}$ is the pumped storage capacity in the period $t$, $P_{PS,t} \geq 0$ is discharge power generation, $P_{PS,t} \leq 0$ is pumped storage, $P_{PS_{max}}$ is the pumped storage rated output upper limit, $P_{PS_{min}}$ is the pumped storage rated output lower limit, $E_r$ is the upper reservoir capacity in the $t$th period, $\Delta E_r$ is the change of storage capacity, $E_{\text{max}}$ is the maximum reservoir capacity and $E_{\text{min}}$ is the minimum upper reservoir’s capacity, and $\eta_g$, $\eta_d$ is the power generation efficiency and pumping efficiency.

3. Beetle Antennae Search Algorithm

Beetle antennae search algorithm (BAS) [4] is a novel intelligent optimization algorithm based on the principle of the beetle foraging in 2017. It can improve the speed of optimization significantly. Following the biological behavior of the beetle, the following modeling steps are abstracted:

1) Created and normalize the random vector in the direction of the antennae

\[
\tilde{b} = \frac{\text{rands}(k,1)}{\|\text{rands}(k,1)\|}
\]

Where \text{rands} is a random function and K is a dimension

2) Create space coordinates for the left and right antenna

\[
\begin{align*}
x_{rt} & = x' + d \times \tilde{b} / 2 \\
x_{lt} & = x' + d \times \tilde{b} / 2 \quad (t=1,2,\ldots,n)
\end{align*}
\]

Where $x_{rt}$ represents the positional coordinates of the right antennae at the $t$th iteration, $x_{lt}$ represents the positional coordinates of the left antennae at the $t$th iteration, $x'$ is the centroid coordinate at the $t$th iteration between the two antennas, and $d$ represents the distance between the two antennas.

3) According to the function $f$ to be optimized, find the value of the left and right two antennas and update the position of the beetle

\[
x^{t+1} = x' - \delta^t \times \tilde{b} \times \text{sign}(f(x_{rt}) - f(x_{lt}))
\]

Where $\delta^t$ is the step factor of the $t$th time, sign() is a symbol function.

4) The step factor $\delta^t$ is used to control the search ability, so the initial step size should be as large as possible so that it can cover the search area and avoid falling into the local optimal solution. This paper adopts the linear decreasing method to ensure the accuracy of the search:
\[ \delta^{\text{net}} = \delta^i \times \text{eta} \] (17)

Where the \text{eta} attenuation coefficient belongs to the number between [0, 1], and the closer to 1, the better, generally \( \text{eta} = 0.95 \).

4. Simulation experiments and analysis

4.1. Day-ahead scheduling with minimum volatility in complementary system

The experimental design of this paper is based on a complementary test system consisting of a wind power station with a 350 MW installed capacity, a solar power plant with a 50 MW installed capacity, a conventional hydropower station and a pumped storage power station. In the current dispatching phase, 1 day is divided into 24 during the time period. Wind power, solar power and load forecasting data are shown in Table 1 and Figure 1-2.

| Time period | Wind power | Solar power | Load | Wind power | Solar power | Load |
|-------------|------------|-------------|------|------------|-------------|------|
| 1           | 271        | 0           | 999  | 13         | 122         | 38.62| 1205 |
| 2           | 280        | 0           | 1000 | 14         | 127         | 35.7 | 1194 |
| 3           | 230        | 0           | 993  | 15         | 116         | 31.97| 1199 |
| 4           | 212        | 0           | 989  | 16         | 140         | 24.85| 1188 |
| 5           | 220        | 8.69        | 1010 | 17         | 152         | 17.7 | 1321 |
| 6           | 167        | 18.59       | 1023 | 18         | 110         | 8.6  | 1571 |
| 7           | 159        | 24.74       | 1248 | 19         | 120         | 0    | 1708 |
| 8           | 170        | 28.86       | 1380 | 20         | 170         | 0    | 1690 |
| 9           | 131        | 34.86       | 1595 | 21         | 143         | 0    | 1618 |
| 10          | 106        | 38.5        | 1560 | 22         | 188         | 0    | 1488 |
| 11          | 112        | 39.2        | 1416 | 23         | 210         | 0    | 1338 |
| 12          | 79         | 39.37       | 1311 | 24         | 185         | 0    | 1175 |

Figure 1 Load forecasting
During the dry season, for hydro power and pumped storage, the adjustable output of conventional hydro power station is from 100 to 130 MW. When matching a pumped storage power station with a maximum output of 30MW, the scheduling results of the optimal system are shown in Fig. 3.

From the optimization scheduling results in Figure 3, it can be seen that compared with wind and solar power alone, the combined output power is more reliable and stable, which eliminates the disadvantages of intermittent power supply fluctuations to some extent. The variance of the sum of wind power plant and the solar power station’s output is 1762.6, and the peak-to-valley difference is 166.4MW. However, the optimized complementary system output power fluctuation variance is only 207.4, and the peak-to-valley difference is reduced to 72.4MW, which greatly reduces the impact of wind and light on the grid, strengthens water resource’s utilization and increase the renewable energy’s
penetration rate. According to the observation in figure 1, the sum of wind and solar power output declined rapidly at about 18 points. Meanwhile, pumped storage energy rapidly increased power output, but due to the limitation of 30MW capacity, the overall output curve of the complementary system still showed a downward gap. When the pumped storage capacity is increased to 50MW, the scheduling results are shown in Figure 4 below. As the pumped storage capacity keeps increasing, the optimization results become more and more ideal.

**Figure 4** (50MW pumping, 100–130MW hydropower during the dry period)

4.2. Day-ahead scheduling with minimum equivalent load volatility

In order to further reduce the peak-to-valley difference of the equivalent load that the thermal power unit needs to bear after complementary system’s connection to power grid and reduce the frequent adjustment of the thermal power unit’s power generation output. The simulation experiment still arranged wind farm and solar power station to generate electricity at full capacity according to their predicted values, and hydropower station to generate electricity in step shape with frequent electricity consumption in peak period and few electricity consumption in low period, which is consistent with the parameters of the previous section. When the maximum output of pumped storage is 100MW, the optimal scheduling results are shown in Figure 4.

**Figure 5** Complementary system output scheduling results (100MW pumping)
As shown in Figure 5, the power load is in the low valley period from 0 to 5 o'clock, while the wind farm is in the maximum output period of the day. At this time, the dispatching result of pumped storage is to pump energy at maximum power, and the wind’s potential energy is stored into water energy. During the early and late peak hours, the wind power is weak. At this time, the pumped storage is discharged at maximum power, and the water’s potential energy is converted into electric energy. It is obvious that the model optimization result is in line with the actual situation. Facing with the peak-to-valley difference of 719MW, the regulating capacity of 100MW pumped storage is somewhat helpless. Although the peak valley difference of equivalent load is reduced to 638.2MW through optimization and the volatility variance is reduced by 56%, there is still a certain peak valley difference in the equivalent load for thermal power unit. When the pumped storage capacity’s installed capacity increases to 300MW, the optimized scheduling result is shown in Figure 7.

![Figure 6](image)

**Figure 6** Complementary system output scheduling results (300MW pumping)

From the Figure 6, we can see that when the maximum output is increased to 300MW, the system’s tracking load curve becomes more stable, and the equivalent load to the thermal power unit is almost constant after the complementary system’s connection to the power grid, which further indicates that the thermal power unit basically does not need to adjust the peak and valley fluctuation of the load.

5. Conclusion

Aiming at the problem of grid stability fluctuation caused by solar power and a wide range of wind and solar power’s connection to the power grid, this paper analyzes the complementary characteristics of the wind power, solar power, hydro power and pumped storage power, then combines them to form a complementary power generation system. Considering multiple energy constraints, there establishes two optimization scheduling models with the minimum output power volatility of the wind-water storage system and the minimum volatility of the thermal power unit equivalent load. Considering the advantages of the algorithm such as easy implementation and fast convergence, using the beetle antennae algorithm to solve the models. The simulation results indicate that the proposed scheduling models can eliminate the power grid’s stability problem caused by wind-solar grid-connection to a certain extent and obtain relatively stable power output of the complementary system.
References

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