Economic dispatch of WT-PV-ES with cogeneration in abnormal regulatory domain

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Abstract: The combined operation of cogeneration, distributed generation and energy storage can effectively meet the electrical and heat load requirements in the northern region, but its economic dispatching problem needs to be solved urgently. An economic dispatch model of WT-PV-ES with heat and power in abnormal regulatory domain is built considering economic cost and environmental cost. Meanwhile, an improved black hole algorithm is proposed, which applied the global search mechanism to improve the search efficiency and ability of optimization. The IEEE30 power distribution system and 6 node heat system are used for simulation. It is verified that the correctness of the proposed model and method.

1. Introduction
During winter heating in northern China, large-scale energy storage system (ES) can store the excess electricity/thermal energy released by the unit during the peak load period, and supplement the power generation during the peak load period, so as to relieve the peaking pressure of the distribution network [1-3]. However, increase the economic burden, ES grid will lead to the power grid for cogeneration units in abnormal control domain scenery store joint economic scheduling problem. In comparison, the black hole algorithm (BHA) has certain advantages in solving the joint economic scheduling model of wind-solar storage in the abnormal control region containing cogeneration units, but it also has disadvantages such as poor global search ability and less solution diversity [4-6].

2. Economic dispatch of wind and solar energy storage with cogeneration unit

2.1 The principle of joint economic operation of wind and solar energy storage in abnormal control area
This paper mainly uses the extraction type cogeneration unit for analysis [7-8]. Cogeneration units generally meet load demand in the way of "using heat to determine power", but their peak load regulation capacity is limited, resulting in excessive output at night load trough, difficulties in wind and light connection, serious wind and light abandoning phenomenon [9].

2.2 joint output model of wind and solar energy storage
If the wind and light output is higher than the load demand, the energy storage is in the charging state, and $\Delta P_{ES}(t)$ is less than 0; if the wind and light output is lower than the load demand, the energy storage is in the discharging state, and $\Delta P_{ES}(t)$ is greater than 0. The corresponding $t$ time storage energy can be
expressed as:

\[ E_{ES}(t) = \begin{cases} E_{ES}(t-1) - \Delta P_{ES}(t-1) \times 1 & \Delta P_{ES}(t-1) \geq 0 \\ E_{ES}(t-1) - \zeta \Delta P_{ES}(t-1) \times 1 & \Delta P_{ES}(t-1) < 0 \end{cases} \]  \hspace{1cm} (1) \]

In the formula, \( E_{ES}(t) \) represents the stored energy at the time of \( t \); \( \zeta \) represents the charging efficiency of the energy storage battery.

3. Formatting the text

3.1 objective function

3.1.1 Economic dispatching cost of wind energy storage

\[
\begin{align*}
C_i &= C_m + C_{CHP} + C_W + C_L + C_{ES} \\
C_m &= C_{Pi} + C_{Hi} \\
C_{Pi} &= a_i + b_i P_i + c_i P_i^2 + d_i \sin \left( e_i \left( P_i^{\min} - P_i \right) \right) \\
C_{CHP} &= a_{ji} + b_{ji} O_i + c_{ji} O_i^2 + d_{ji} H_i + e_{ji} H_i^2 + f_{ji} O H_i \\
C_{Hi} &= a_{ni} + b_{ni} T_i + c_{ni} T_i^2
\end{align*}
\]  \hspace{1cm} (2)

In the formula, \( C_{CHP} \) represents the cost of conventional unit and cogeneration fuel; \( C_W \) and \( C_L \) represent the cost of wind and light power generation respectively; \( C_{ES} \) represents the cost of energy storage; \( C_{Pi} \) and \( C_{Hi} \) represent the cost of pure generator unit and pure heating unit respectively; \( P_i \) represents the output of pure generator unit; \( O_i \) and \( H_i \) represent the power output and thermal output of cogeneration unit respectively; \( T_i \) represents the output of pure heating unit.

3.1.2 Environmental cost of economic dispatching of wind energy storage

\[
C_Z = K_E \left[ \sum_{i=1}^{T} \sum_{m=1}^{N_m} e_{mi}(P_{mi,t}) + \sum_{i=1}^{N_{CHP}} e_{CHP}(P_{CHP,t}, q_{CHP}) \right] \hspace{1cm} (3)\]

In the formula, \( K_E \) represents the price of unit carbon emission; \( e_{mi} \) and \( e_{CHP} \) represent the carbon emission function of the \( ith \) conventional unit and the \( ith \) cogeneration unit respectively.

3.2 constraint condition

3.2.1 Power balance constraint

\[
\sum_{i=1}^{N} p_{mi,t} + \sum_{i=1}^{N_{CHP}} p_{CHP,i} + \sum_{i=1}^{N_{W-L}} p_{W-L,i} + \sum_{i=1}^{N_{ES,T}} p_{ES,t} = p_{load,t} \]  \hspace{1cm} (4)

In the formula, \( p_{mi,t} \) represents the output of the \( ith \) conventional unit at the time of \( t \); \( p_{W-L,i} \) represents the output power of the \( ith \) typhoon and optical unit at the time of \( t \); \( p_{ES,T} \) represents the charge and discharge power of the \( ith \) energy storage device at the time of \( T \); \( p_{load,t} \) represents the load demand at the time of \( t \).

3.2.2 output constraint of conventional unit

Upper and lower limits of conventional unit output:

\[
p_{\text{min}}^{mi} \leq p_{mi,t} \leq p_{\text{max}}^{mi} \]  \hspace{1cm} (5)

In the formula, \( p_{\text{min}}^{mi} \), \( p_{\text{max}}^{mi} \) respectively represent the upper and lower limits of output of the \( ith \)
conventional unit at the time of $t$.

Conventional unit climbing constraints:

\[
\begin{align*}
    p_{ui,i} - p_{ui,i-1} &\leq p_{ui}^{up} \\
    p_{ui,i-1} - p_{ui,i} &\leq p_{ui}^{down}
\end{align*}
\] (6)

In the formula, $p_{ui}^{up}$, $p_{ui}^{down}$ represent the maximum up and down ramp rates of the $ith$ conventional unit respectively.

3.2.3 Constraints on Cogeneration Units

Thermal output restriction of cogeneration unit:

\[
q_{CHPI,i}^{min} \leq q_{CHPI,i} \leq q_{CHPI,i}^{max}
\] (7)

In the formula, $q_{CHPI,i}^{min}$, $q_{CHPI,i}^{max}$ respectively represent the upper and lower limits of the thermal power rate of the $ith$ cogeneration unit.

Power output restriction of cogeneration unit:

\[
\begin{align*}
    p_{CHPI,i} &= \max \left(p_{CHPI}^{min} - C_v q_{CHPI,i}, C_m q_{CHPI,i} + C_k\right) \\
    p_{CHPI,i} &\leq p_{CHPI,\max} - C_v q_{CHPI,i}
\end{align*}
\] (8)

Thermal climbing restriction of cogeneration unit:

\[
\begin{align*}
    q_{CHPI,i-1} - q_{CHPI,i} &\leq q_{CHPI,i}^{down} \\
    q_{CHPI,i} - q_{CHPI,i-1} &\leq q_{CHPI,i}^{up}
\end{align*}
\] (9)

In the formula, $q_{CHPI,i}^{up}$ and $q_{CHPI,i}^{down}$ respectively represent the upper and lower limits of the thermal power ramp rate of the $ith$ cogeneration unit.

Power ramp restriction of cogeneration unit:

\[
\begin{align*}
    p_{CHPI,i} - p_{CHPI,i-1} &\leq p_{CHPI,\max} - C_v \left(q_{CHPI,i} - q_{CHPI,i-1}\right) \\
    p_{CHPI,i-1} - p_{CHPI,i} &\leq p_{CHPI,\max} - C_v \left(q_{CHPI,i-1} - q_{CHPI,i}\right)
\end{align*}
\] (10)

In the formula, $q_{CHPI,i}^{up}$, $q_{CHPI,i}^{down}$ respectively represent the upper and lower limits of the power ramp rate of the $ith$ cogeneration unit.

4. Based on the improved black hole algorithm for joint economic scheduling of wind and solar energy storage

4.1 Global search mechanism

The global search mechanism of PSO is introduced to improve the BHA algorithm.

If $l_i \geq P$, then:

\[
\begin{align*}
    v_{i+1} &= \omega v_i + c_1 r_1 \left(x_i - x_i^*\right) + c_2 r_2 \left(x_i - x_i^*\right) \\
    x_{i+1} &= x_i + v_{i+1}
\end{align*}
\] (11)

If $l_i < p$, then:

\[
\begin{align*}
    x_{i+1} &= x_i^* + D_i^* \\
    D_i^* &= 2R \left(r_i^* - 0.5\right)
\end{align*}
\] (12)
In the formula, \( l_i \) represents the corresponding probability of the \( i \)-th star in the \( t \)-th iteration, and the value range is \([0,1]\); \( p \) represents the probability threshold of black hole absorbing stars; \( r_i \) represents the random number between \([0,1]\); \( R \) represents the radius of black hole; \( D_t \) represents the random number between \([0,1]\).

\[
\omega = \omega_{\text{max}} - (\omega_{\text{max}} - \omega_{\text{min}}) t / t_{\text{max}} \quad (13)
\]

In the formula, \( \omega \) represents the inertia weight, and \( t \) represents the current number of iterations.

\[
\begin{cases}
  v_{\text{min}} \leq v^i_t \leq v_{\text{max}} \\
v_t = (x_{\text{max}} - x_{\text{min}}) / M \\
v_{\text{min}} = -v_{\text{max}}
\end{cases} \quad (14)
\]

In the formula, \( v_{\text{min}} \) and \( v_{\text{max}} \) represent the maximum and minimum speed of stars respectively; \( M \) represents the constraint value to limit the maximum speed of stars. If the speed of stars exceeds the speed boundary, the speed of stars is calculated at the maximum or minimum speed.

4.2 Joint economic scheduling based on improved black hole algorithm
The corresponding fitness function can be expressed as:

\[
F_i(t) = \begin{cases} 
  f_i(t) & f_i(t) \geq 0 \\
  \text{abs}(f_i(t)) & f_i(t) < 0
\end{cases} \quad (15)
\]

In the formula, \( f_i(t) \) represents the adaptive value of the star. The smaller the adaptive value is, the lower the economic cost is. In the iteration process, if the adaptive value of new stars is better than that of black holes, black holes will be formed with the new stars as the center to attract other stars; if the adaptive value of new stars exceeds the boundary of black holes, the boundary formula of black holes can be expressed as follows:

\[
R(t) = \frac{F_B}{\sum_{i=1}^{N} F_i(t)} \quad (16)
\]

In the formula, \( F_B \) represents the adaptive value of the current black hole.

5. Example simulation
The examples in this paper are mainly divided into 3 cases for simulation:

Case 1: only the normal unit operates separately;

Case 2: the system is equipped with conventional unit, cogeneration unit and WT-PV joint operation;

Case 3: the system is equipped with conventional units, cogeneration units and wind and solar energy storage combined operation

Select a certain time (take 17:00-18:00 as an example) the optimal output of conventional units and cogeneration units in the grid under different conditions as shown in Table 1.

| output /GW | Situation 1 | Situation 2 | Situation 3 |
|------------|-------------|-------------|-------------|
| \( P_1 \)  | 0.7532      | 0.4928      | 0.4928      |
| \( P_2 \)  | 0.5157      | 0.3407      | 0.3407      |
| \( P_3 \)  | 0.4469      | 0.2243      | 0.2243      |
| \( P_4 \)  | 0.3274      | 0.1611      | 0.1611      |
Tab. 1. System cost in different situations

| Situation | Economic cost / Ten thousand yuan | Environmental costs / Ten thousand yuan | Total cost / Ten thousand yuan |
|------------|----------------------------------|----------------------------------------|-------------------------------|
| 1          | 927.83                           | 81.96                                  | 1009.79                       |
| 2          | 916.45                           | 60.32                                  | 976.77                        |
| 3          | 909.17                           | 59.51                                  | 968.68                        |

It can be seen from table 1 and table 2 that after the cogeneration unit is connected to the grid, the output of conventional unit is significantly reduced. Because the cogeneration unit is relatively clean, its environmental pollution is significantly reduced. During the peak load period, it is difficult to adjust the peak load due to the climbing constraints of conventional units and cogeneration units, so it is difficult to meet the demand of load change. At this time, the grid is in the abnormal regulation domain, and the ES auxiliary grid operation needs to be adjusted.

It can be seen from Figure 1 that PSO has faster calculation efficiency, but the optimal fitness is significantly worse than BHA. At the same time, due to the global search mechanism in IBHA, on the basis of ensuring faster iteration speed, the algorithm avoids falling into local optimization, obtains stronger optimization ability, and ensures diversity of understanding, which proves that the algorithm has certain correctness and effectiveness. Therefore, the improved black hole algorithm can effectively solve the economic scheduling problem of wind energy storage combined operation with cogeneration units, and provide an effective operation scheme, which can be applied to practical projects.

6. conclusion
1) on the premise of considering the system economy, the grid connection of energy storage system can reduce the wind and light wave dynamics, improve the power grid regulation capacity, and meet the needs of users.
2) the improved black hole algorithm with the global search mechanism has better computing efficiency and optimization ability, and can effectively solve the economic scheduling problem of wind energy storage combined operation with cogeneration unit, and can provide effective decision-making scheme for engineers.

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