Multi-objective coordinated scheduling of anomalous control domain with electric/thermal energy storage and translatable load

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Abstract: Difficulties in the consumption of new energy such as wind and light are one of the main reasons for the low penetration rate of distributed power. The multi-objective coordinated scheduling model of anomalous control domain with electric/thermal energy storage and translatable load is constructed from the aspects of energy utilization, system network loss and environmental pollution cost. A hybrid random black hole algorithm is proposed to improve the algorithm by using global search mechanism. The example analysis is carried out by IEEE30 node power distribution system. The simulation results show that the coordinated optimization of energy storage and translatable load can effectively improve energy efficiency, reduce system network loss and environmental pollution cost, and verify the rationality of the proposed model.

1. Introduction
In the abnormal regulation domain, by coordinating and controlling the source and load, it can increase the grid's ability to accept wind, light and other energy sources, improve the operating efficiency of the power supply side, and reduce the wind abandonment caused by wind and light uncertainty. Relatively speaking, the random black hole algorithm (RBHA) has certain advantages in solving the anomalous regulatory domain coordination scheduling model with electric/thermal energy storage and translatable load, but there are still some shortcomings such as poor global search ability and less diversity of solutions [1-3].

In this paper, the multi-objective coordinated scheduling problem of abnormal regulation domain with electric/thermal energy storage and translatable load is considered. The multi-objective coordinated scheduling model is established by considering the degree of load translation fitting, energy utilization, system network loss and environmental pollution cost. A hybrid random black hole algorithm is used to solve the problem. The simulation is carried out according to the IEEE 30-node power distribution system to verify the correctness and effectiveness of the proposed scheduling model and optimization method.
2. translatable load model
According to the classification of response characteristics, load can be divided into transferable load, translatable load and reducible load [4]. This paper mainly studies translatable load.

2.1. objective function
The main objective of translating load is to maximize the fitting degree between the load curve and the target load curve after translating load curve. The specific formula can be expressed as follows:

\[
\begin{align*}
    \min & \sum_{t=1}^{T} (L_t - L_{ob, t}) \\
    L_t &= L_{in, t} + L_{out, t} - L_{be, t}
\end{align*}
\] (1)

In the formula, \(T\) denotes the scheduling period; \(L_t\) and \(L_{ob, t}\) denote the translation load and the target load in the \(t\) period; \(L_{in, t}\) and \(L_{out, t}\) denote the turn-in and turn-out load in the \(t\) period respectively. Because the power supply time of different loads is different, and the input and output loads before the \(t\)-period may affect the load of that period, it is necessary to consider the influence of the power supply duration equal to or greater than that of the input and output loads during a dispatching period when translating the load. The corresponding formula can be expressed as [5-6]:

\[
\begin{align*}
    L_{in, t} &= \sum_{k=t}^{m_{SL1}} \sum_{t'=1}^{k} x_{k, t', t'} P_{k, t} + \sum_{h=1}^{h_{max}} \sum_{k=t-h}^{m_{SL2}} \sum_{t'=1}^{k} x_{k, t', t'} P_{h+k, k} \\
    L_{out, t} &= \sum_{k=1}^{m_{SL1}} \sum_{t'=1}^{k} x_{k, t', t'} P_{k, t} + \sum_{h=1}^{h_{max}} \sum_{k=t-h}^{m_{SL2}} \sum_{t'=1}^{k} x_{k, t', t'} P_{h+k, k}
\end{align*}
\] (2)

In the formula, \(m_{SL1}\) denotes the number of translatable loads; \(m_{SL2}\) denotes the number of translatable loads whose power supply duration is longer than a dispatching period; \(h_{max}\) denotes the upper limit of power supply duration; \(x_{k, t', t'}\) denotes the number of translatable loads of type \(k\) from \(t\) to \(t'\); \(P_{k, t}\) and \(P_{h+k, k}\) respectively represent the power of class \(k\) translational load at time period 1 and time period \(h+1\).

2.2. Constraints

2.2.1. translation time constraints. In the formula, \(S_{k, t}\) represents the earliest transition period of type \(k\) translatable load, and \(d_{k, t}\) represents the translation margin of type \(k\) translatable load.

\[
\begin{align*}
    \forall t' < s_{k, t}, & \quad x_{k, t, t'} = 0 \\
    \forall t' > (s_{k, t} + d_{k, t}), & \quad x_{k, t, t'} = 0
\end{align*}
\] (3)

2.2.2. translation constraints. In the formula, \(x_{k, t}\) represents the number of translatable loads of class \(k\) in the \(t\)-period, and the total amount of loads before and after translations should be guaranteed to remain unchanged in a dispatching cycle.

\[
\begin{align*}
    \forall t, t', k, & \quad x_{k, t} \geq 0 \\
    x_{k, t} = \sum_{t=1}^{T} x_{k, t, t'}
\end{align*}
\] (4)

3. Multi-objective Coordination Scheduling Model

3.1. objective function
3.1.1. Energy Utilization Rate. Wind and photovoltaic power generation can effectively increase the tightness of load curve with wind and photovoltaic output by setting the maximum power principle and optimizing dispatching translation load curve, thus maximizing the absorption rate of wind and photovoltaic. The objective function of energy efficiency $A$ can be expressed as:

$$
A(t) = \frac{\sum_{i=1}^{24} (P'^{W}_{i} + P'^{L}_{i})}{\sum_{i=1}^{24} (P'^{W}_{i} + P'^{L}_{i} + P'^{other}_{i})}
$$ (5)

In the formula, $P'^{W}_{i}$, $P'^{L}_{i}$, $P'^{other}_{i}$ represent the output of wind, light and other distributed power sources in $t$ period respectively. Because wind and light can be used as discrete control variables, this paper divides into 24 periods to measure energy efficiency. The greater the energy efficiency, the higher the corresponding grid income.

3.1.2. System Network Loss. As the energy storage device will produce certain losses in the charging and discharging process, the objective function of system network loss can be expressed as:

$$
P_{\text{Loss}}(t) = \sum_{i=1}^{24} (P_{\text{L.Lo}}^{i} + P_{\text{E.Lo}}^{i})
$$ (6)

In the formula, $P_{\text{Loss}}(t)$ represents the total network loss of the system in time period $t$; $P_{\text{L.Lo}}^{i}$ is power line loss at time $t$, $P_{\text{E.Lo}}^{i}$ is charge and discharge energy loss at time $t$ of energy storage device. The lower the loss of system network, the lower the corresponding network cost.

3.1.3. Cost of Environmental Pollution. Wind and photovoltaic distributed generators are clean energy sources, which can achieve zero pollution in operation. However, other distributed generators, such as fuel cell power generation, will produce some polluted gases. Their objective functions are as follows:

$$
C(t) = \sum_{i=1}^{N_{k}} \sum_{k=1}^{K} \alpha_{i} \frac{P_{G}^{i}}{\eta_{a} \eta_{b}} \beta_{k}
$$ (7)

In the formula, $C$ denotes the cost of environmental pollution; $\alpha_{i}$ denotes the treatment cost of the class $k$ polluted gas; $P_{G}^{i}$ denotes the purchase of electricity in the $t$ period; $\eta_{a}$, $\eta_{b}$ denote the power generation efficiency and transmission efficiency of power plants respectively; $\beta_{k}$ denotes the emission coefficient of the class $k$ polluted gas. The lower the cost of pollution discharge, the higher the degree of environmental friendliness.

3.2. Constraint

3.2.1. Power Balance Constraints. $P_{\text{DG},t}$ represents the output power of the distributed power supply of stage I at time $t$. $P_{\text{ES},t}$ denotes the charging and discharging power of the first energy storage device in the $t$ period; $P_{\text{load},t}$ denotes the load demand in the $t$ period.

$$
\sum_{i=1}^{N_{DG}} P_{\text{DG},i} + \sum_{i=1}^{N_{ES}} P_{\text{ES},i} = P_{\text{load},t}
$$ (8)

3.2.2. Wind and Light Capacity Constraints. In the formula, $P_{W}$, $P_{L}$ represent the upper and lower limits of storage capacity of electricity storage device.

$$
0 \leq P_{W} \leq P_{W_{\text{max}}}
$$

$$
0 \leq P_{L} \leq P_{L_{\text{max}}}
$$ (9)

3.2.3. Energy Storage System Constraints. Charge and discharge constraints of storage devices:
\[
\begin{cases}
E_{E_{\text{min}}} \leq E_{E_{\text{ES}}} (t) \leq E_{E_{\text{ES}}} \\
0 \leq E_{E_{\text{ES}}} \leq E_{E_{\text{Bmax}}}
\end{cases}
\] (10)

In the formula, \( E_{E_{\text{ESmax}}} \) and \( E_{E_{\text{ESmin}}} \) respectively represent the upper and lower limits of storage capacity of the storage device. Operation constraints of heat storage devices:

\[
\begin{align*}
S'_i - S'_{t-i} & \leq P^{\text{max}}_{E_{\text{ESi}}, t} \\
S'_i - S'_{t-i} & \leq P^{\text{max}}_{E_{\text{ESi}}, t} \\
S'_i & \leq S'_{\text{max}} \\
\sum_{i=1}^{T} P_{E_{\text{ESi}}, t} & = 0
\end{align*}
\] (11)

In the formula, \( S \) represents the heat storage of the heat storage device of platform \( i \) at time period \( t \); \( P^{\text{max}}_{E_{\text{ESi}}, t} \) and \( P^{\text{max}}_{E_{\text{ESi}}, t} \) respectively represent the upper and lower limits of heat storage and exothermic power of the heat storage device in the time period \( t \); \( P_{E_{\text{ESi}}, t} \) represents the heat storage and exothermic power of the heat storage device in the time period \( t \). \( S'_{\text{max}} \) represents the upper limit of heat storage capacity of the heat storage unit of platform \( i \).

4. Multi-objective Coordination Scheduling Based on Hybrid Random Black Hole Algorithms

A global search mechanism is introduced into RBHA to improve the corresponding parameters, and a hybrid random black hole algorithm is proposed.

4.1. Global Search Mechanism

If \( l_i < p \), then:

\[
\begin{align*}
\psi'_{i+1} & = \omega \psi'_{i} + c_1 r_1 \left( \chi'_{g} - \chi'_{i} \right) + c_2 r_2 \left( \chi'_{p} - \chi'_{i} \right) \\
\chi'_{i+1} & = \chi'_{i} + \psi'_{i+1}
\end{align*}
\] (12)

If \( l_i < p \), then:

\[
\begin{align*}
\chi'_{i+1} & = \chi'_{g} + D'_i \\
D'_i & = 2R \left( r_3 - 0.5 \right)
\end{align*}
\] (13)

In the formula, \( l_i \) represents the probability corresponding to the \( i \)th astral body in the \( t \)th iteration, whose value range is \([0,1]\); \( P \) is the probability threshold of black hole absorbing astral body; \( r_3 \) represents random Numbers between \([0,1]\); \( R \) is the radius of the black hole; \( D'_i \) represents random Numbers between \([0,1]\).

\[
\omega = \omega_{\text{max}} - \left( \omega_{\text{max}} - \omega_{\text{min}} \right) t / t_{\text{max}}
\] (14)

In the formula, \( \omega \) denotes inertia weight and \( t \) denotes current iteration times.

\[
\begin{align*}
\psi_{\text{min}} & \leq \psi'_{i} \leq \psi_{\text{max}} \\
\psi_{\text{max}} & = \left( \chi_{\text{max}} - \chi_{\text{min}} \right) / M \\
\psi_{\text{min}} & = -\psi_{\text{max}}
\end{align*}
\] (15)

In the formula, \( \psi_{\text{min}} \) and \( \psi_{\text{max}} \) represent the maximum and minimum velocities of astral bodies respectively; \( M \) represents the constraints to limit the maximum velocities of astral bodies. If the velocities of stars exceed the velocity boundary, the maximum or minimum velocities of astral bodies are calculated.
4.2. Multi-objective coordination scheduling model based on HRBHA

Aiming at multi-objective coordinated dispatching problem in abnormal control domain with electric/thermal energy storage and translatable load, the corresponding fitness function can be expressed as follows:

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

(16)

In the formula, \( f_i(t) \) represents the adaptive value of the astral body. If the adaptive value of new astral bodies is better than that of black holes in the iteration process, the black holes formed around the new stars will continue to attract other astral bodies. If the adaptive value of new astral bodies exceed the boundary of a black hole, in order to keep the total number of black holes will remain unchanged and the astral bodies will be swallowed by the black hole. The boundary formula can be expressed as follows:

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

(17)

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

5. Examples simulation

In the multi-objective coordinated dispatch of abnormal control domain with electric/thermal energy storage and translatable load, the algorithm parameters are set under the premise of considering energy utilization, system network loss and pollution cost comprehensively, so as to improve its applicability. The specific parameter settings are shown in Table 1.

| Number of particles | Number of iterations | Black hole radius | Probability threshold | \( \omega_{\text{min}} \) | \( \omega_{\text{max}} \) |
|---------------------|----------------------|-------------------|----------------------|----------------|----------------|
| 100                 | 300                  | 0.01              | 0.3                  | 0.95          | 0.45          |

The translatable loads selected in this paper are mainly divided into four categories: clothes dryer, washing machine, water heater and air conditioner. The demand for translatable load accounts for 20% of the total load. Among them, the continuous working time of clothes dryer is 1 hour and the number of equipment is 900; the continuous working time of washing machine is 2 hours and the number of equipment is 2500; the continuous working time of water heater is 1 hour and the number of equipment is 1000; the continuous working time of air conditioner is 3 hours and the number of equipment is 1800. The number of translatable loads in each period is shown in Fig 1.

Fig 1. The number of shiftable loads in different periods

Fig 2. Curves before and after electric and heat loads shifting

The electric and thermal load curves before and after translation are shown in Fig 2. It can be seen that the peak-valley difference of electric and thermal loads decreases significantly, and load translation can effectively achieve the effect of peak-cutting and valley filling.
Therefore, the coordinated dispatch of energy storage and translatable load in the abnormal regulation domain has a good economy and environmental protection, and can achieve high efficiency of energy utilization in the operation of power grid.

6. conclusion
1) Load translation can effectively reduce the difference between peak and valley load, and achieve the effect of peak-cutting and valley-filling.
2) Energy storage grid-connected can reasonably restrain wind and light fluctuations, increase wind and light access space, and reduce the phenomenon of wind and light abandonment.
3) Coordination of energy storage and translatable load dispatching can further improve energy utilization, system economy and power quality, which has certain practical reference value for day-ahead dispatching.

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